

1. REPORT NUMBER CA11-1204	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment		5. REPORT DATE 01/01/2012
7. AUTHOR Matthew Barth, Thomas Durbin, J. Wayne Miller, Kent Johnson Co: R.L. Russell ,G. Scora		6. PERFORMING ORGANIZATION CODE
9. PERFORMING ORGANIZATION NAME AND ADDRESS College of EGINEERING-Center for Environmental Research and Technology University of California Riverside, CA 92507		8. PERFORMING ORGANIZATION REPORT NO.
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation Division of Research and Innovation, MS-83 1227 O Street Sacramento, CA 95814		10. WORK UNIT NUMBER 191
		11. CONTRACT OR GRANT NUMBER 65A0282
		13. TYPE OF REPORT AND PERIOD COVERED Final - July 1, 2008 - June 30, 2011
		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

Gaseous and particle emissions from construction engines are an important fraction of the total air pollutants and are gaining increasing regulatory attention. Quantification of NOx and PM is necessary to inventory the contribution of the construction equipment, such as used by Caltrans, to atmospheric loadings, particularly for those projects in non-attainment or maintenance areas. At present, however, there is no model mutually accepted by Caltrans and regulatory agencies that can be used for the estimation of construction emissions or the development of appropriate regulations. This is due in part to a lack of emissions data from construction equipment under in-use operating conditions. The lack of a sound scientific basis for regulation has resulted in legal cases and other obstacles that could potentially delay or inhibit important transportation projects.

17. KEY WORDS Emissions, Construction Equipment, Transportation Projects	18. DISTRIBUTION STATEMENT No restrictions
19. SECURITY CLASSIFICATION (of this report) Unclassified	20. NUMBER OF PAGES 47
	21. COST OF REPORT CHARGED

Final Report

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

January 2012

Prepared for:

**California Department of Transportation (Caltrans)
Division of Research and Innovation
RTA 65A0197**

Contract Number: 65A0282

Principal Investigators: Matthew Barth, Thomas D. Durbin, J. Wayne Miller, Kent Johnson
Co-Authors: Robert L. Russell, George Scora

*College of Engineering-Center for Environmental Research and Technology
University of California
Riverside, CA 92507
(951) 781-5791
(951) 781-5790 fax*

DISCLAIMER STATEMENT

This document is disseminated in the interest of information exchange. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This publication does not constitute a standard, specification or regulation. This report does not constitute an endorsement by the Department of any product described herein.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette, or compact disk. To obtain a copy of this document in one of these alternate formats, please contact: the Division of Research and Innovation, MS-83, California Department of Transportation, P.O. Box 942873, Sacramento, CA 94273-0001.

Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Department of Transportation. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Acknowledgments

This report was prepared at the University of California, Riverside, Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT). The primary contributors to this report include Kent Johnson, Robert Russell, Tom Durbin, George Scora, and Matthew Barth. The authors thank the following organizations and individuals for their valuable contributions to this project. We acknowledge Don Pacocha, Edward O'Neil, and Joe Valdez of CE-CERT for their assistance in carrying out the experimental program. Also, we would like to thank the following: (1) B&B Equipment Rental for renting the first five pieces of equipment and providing a lot where the equipment could be tested under in-use conditions; and (2) Steve McFarland of the County of Riverside who made arrangements for testing two pieces of equipment in Thermal California and the employees there who were very helpful in helping with the setting up the emission measurement equipment and operating the off-road equipment;

Table of Contents

Disclaimer	i
Acknowledgments	i
Table of Contents	ii
Executive Summary	1
1.0 Introduction	2
2.0 Experimental Procedures	2
Emissions Measurement Systems	2
Test Set-up	4
Preliminary Validation Testing	6
Construction Equipment Tested for Emissions	8
3.0 Results	14
4.0 Off Road Equipment Emission Estimator (ORE)	26
Data Analysis	26
ORE Modeling Methodology	30
ORE Graphical User Interface	32
5.0 References	36
Appendix A – Background Information on UCR’s Mobile Emission Lab	38

Table of Tables

Table 2-1: Emissions concentration level comparison between PEMS and MEL 8
 Table 2-2: Equipment Tested 9
 Table 4-1: Description of Equipment Tested..... 31
 Table 4-2: Typical Emission Factors for Each Pollutant under Idling and Working Conditions. 32

Table of Figures

Figure 2-1: Picture of Semtech DS PEMS..... 3
 Figure 2-2: Picture of Semtech DS Exhaust Flow Meter 3
 Figure 2-3: Picture of AVL Micro Soot Sensor with Gravimetric Filter Box on Top..... 4
 Figure 2-4: Yamaha EF2800 Generator for Powering Equipment 5
 Figure 2-5: Emission Analyzers, Generator, and Flow Meter on a 4' by 4' Plastic Pallet..... 6
 Figure 2-6: CE-CERT's Mobile Emissions Laboratory (MEL) 7
 Figure 7: John Deere Backhoe 410J on Vacant Lot in Riverside, California 10
 Figure 2-8: John Deere Backhoe 310SJ on Vacant Lot in Riverside, California 10
 Figure 2-9: John Deere Wheel Loader 644J on Vacant Lot in Riverside, California..... 11
 Figure 2-10: John Deere Backhoe 310SG on Vacant Lot in Riverside, California 11
 Figure 2-11: John Deere Backhoe 410G on Vacant Lot in Riverside, California 12
 Figure 2-12: Komatsu WA470-6 Wheel Loader at Quarry in Thermal, California 12
 Figure 2-13: Caterpillar 928G Wheel Loader at Quarry in Thermal, California..... 13
 Figure 3-1: Emissions from John Deere 410J Backhoe on 12/03/2010..... 15
 Figure 3-2: Emissions from John Deere 310SJ Backhoe on 12/07/2010 16
 Figure 3-3: Emissions from John Deere 644J Wheel Loader on 12/08/2010..... 17
 Figure 3-4: Emissions from John Deere 310SG Backhoe on 12/09/2010 18
 Figure 3-5: Emissions from John Deere 410G Backhoe on 12/10/2010 19
 Figure 3-6: Emissions from Komatsu WA470-6 Wheel Loader on 2/09/2011 20
 Figure 3-7: Emissions from Caterpillar 928G Wheel Loader on 2/10/2011 21
 Figure 3-8: CO₂ and PM emissions from a 2007 Tier 2 John Deere 410 J backhoe. 22
 Figure 3-9: CO₂ and PM emissions from a 2010 Tier 3 John Deere 310 SJ backhoe. 22
 Figure 3-10: CO₂ and PM emissions from a 2007 Tier 3 John Deere 644 J wheel loader. 22
 Figure 3-11: CO₂ and PM emissions from a 2006 Tier 2 John Deere 310 SG backhoe for 1st test.
 23
 Figure 3-12: CO₂ and PM emissions from a 2006 Tier 2 John Deere 310 SG backhoe for 2nd test.
 23
 Figure 3-13: CO₂ and PM emissions from a 2006 Tier 2 John Deere 410 G backhoe. 23
 Figure 3-14: CO₂ and PM emissions from a 2009 Tier 3 Komatsu WA470-6 wheel loader. 24
 Figure 3-15: CO₂ and PM emissions from a 2004 CAT 928G backhoe for 1st test..... 24
 Figure 3-16: CO₂ and PM emissions from 2004 CAT 928G wheel loader for 2nd test. 24
 Figure 3-17: CO₂ and PM emissions from 2004 CAT 928G wheel loader for 3rd test..... 25
 Figure 3-18: Time alignment example showing pattern of emission events across one test. 25

Figure 3-19: Time alignment example showing alignment of emission spikes at a smaller scale. 25

Figure 4-1: This figure shows sample mapped activity data for a back hoe. The green star is the starting location and the red star is the ending location..... 27

Figure 4-2: This figure shows sample mapped activity data for a wheel loader. The green star is the starting location and the red star is the ending location. 27

Figure 4-3: This figure shows sample activity data for a Backhoe..... 28

Figure 4-4: This figure shows sample activity data for a wheel loader. 28

Figure 4-5: This figure shows an example of the separation of the data ranges into idle and work modes. Data colored red is in the idle mode while data colored green is in the work mode. Blue colored data is not incorporated in emission factor calculations..... 29

Figure 4-6: This figure shows sample emission rate data for a wheel loader..... 29

Figure 4-7: This figure shows sample emission rate data for a Backhoe. 30

Figure 4-8: Main window for ORE model..... 33

Figure 4-9: Current parameter display window for ORE Model 34

Figure 4-10: Sample output file from the ORE model 35

Executive Summary

Gaseous and particle emissions from construction engines are an important fraction of the total air pollutants and are gaining increasing regulatory attention. Quantification of NO_x and PM is necessary to inventory the contribution of the construction equipment, such as used by Caltrans, to atmospheric loadings, particularly for those projects in non-attainment or maintenance areas. At present, however, there is no model mutually accepted by Caltrans and regulatory agencies that can be used for the estimation of construction emissions or the development of appropriate regulations. This is due in part to a lack of emissions data from construction equipment under in-use operating conditions. The lack of a sound scientific basis for regulation has resulted in legal cases and other obstacles that could potentially delay or inhibit important transportation projects. In a prior project (Barth, et. al), gaseous emission measurement were made for twelve pieces of construction equipment.

The goal of this research program was to obtain additional construction equipment emissions data with a specific goal of obtaining quantitative particulate matter (PM) data and developing a model to estimate gaseous and PM emissions. The program included two main aspects: 1) in-field emissions and activity measurements; and 2) model development and validation. The emissions measurements were made on a second-by-second basis using a portable emissions measurement system (PEMS) to develop relationships between NO_x and PM and other emissions and fuel use. These emissions data are being used in the development of a model that allows the determination of emissions from different pieces of construction equipment or for construction projects as a whole. The model developed is a user-friendly program that can be readily used by program staff at Caltrans, outside contractors or other government agencies.

Emissions measurements were made for 7 in-use pieces of construction equipment. The equipment includes 4 backhoes and 3 wheel loaders. A fuel-specific emissions model has been developed for the gaseous and particulate emissions that can estimate emissions for Tier 2 or Tier 3 backhoes or wheel loaders. The instrument used to measure PM actually only measures soot directly. A program provided by the instrument manufacturer is used to convert the measured soot to PM by including hydrocarbons, sulfates, etc. which are collected by the standard method of collecting all PM on filter paper over the total length of the test. When PM is collected by the standard method it is not possible to model PM emissions since there is only a single number instead of a g/sec result.

A summary of the major findings and accomplishments of this program are as follows:

- Most construction equipment (of the approximate same size) exhibited similar emission profiles, however their activity differed somewhat;
- There were differences observed between cold-start and warm-start idle emissions among the different equipment;

- Normalizing emission output by fuel results in relatively small variations in emission levels under different levels of load.

1.0 Introduction

The primary purpose of this project is to develop a user-friendly emissions model that can be utilized in the development and implementation of construction equipment regulations. The model was developed from emissions measured on a second-by-second basis and activity as determined by outputs from the electronic control modules for Tier 2 and Tier 3 backhoes and wheel loaders. Thus currently the model is only applicable to equipment of this type.

It is anticipated that as emissions and activity data become available for additional equipment types the model can be modified so that it will have wide applicability and provide a more formal basis for regulatory development. It is important to understand that CE-CERT is already involved with a number of programs with CARB that are forming the basis for non-road regulations in the State of California, and CE-CERT is in the process of formally conducting the evaluation of PEMS units for use in upcoming regulatory work with CARB. With CE-CERT's strong technical background, it is anticipated these emissions results and the resulting model will be widely accepted by a range of shareholders. The development of regulations based on sound science will help the environmental process associated with the implementation of new construction projects. This will in turn facilitate construction projects necessary for the development and maintenance of a transportation system that is safe, efficient and effective. At the same time, a more efficient regulatory process will allow more rapid adoption of regulations that will improve air quality and promote public health, while reducing legal and other costs.

2.0 Experimental Procedures

Emissions Measurement Systems

Over the course of the test program, two different analyzers were utilized for the measurement of the emissions. One analyzer measured all of the gaseous species while the other measured the particulate matter.

The gaseous emissions were measured with a Semtech DS analyzer (see <http://www.sensors-inc.com/>). This system measures NO_x using a UV analyzer, total hydrocarbons (THC) using a flame ionization detector (FID), and carbon monoxide (CO) and carbon dioxide (CO₂) using a non-dispersive infrared (NDIR) analyzer. THC emissions are collected through a line heated to 190°C consistent with the conditions for regulatory measurements. The analyzer provides measurements of the concentration levels in the raw exhaust. A picture of the Semtech DS unit is provided below.

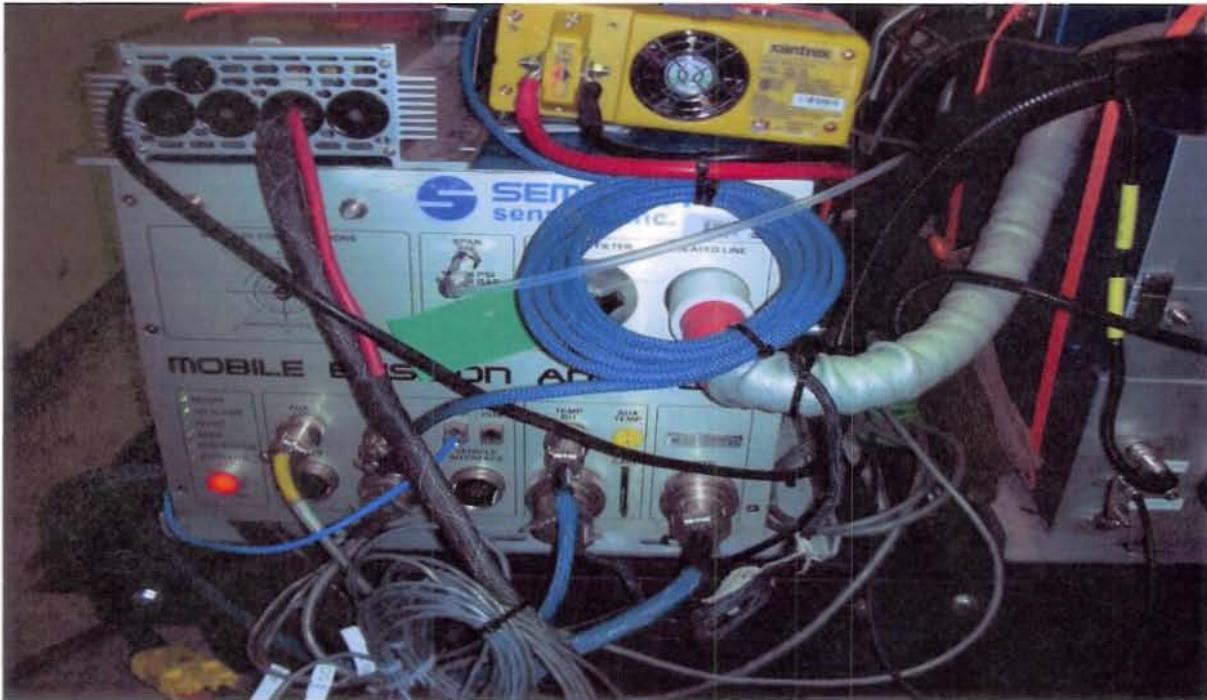


Figure 2-1: Picture of Semtech DS PEMS

A flow meter based on a pitot tube operational principal is used for the measurement of exhaust flow rates. The flow meter is housed in a 3", 4", or 5" diameter pipe that is placed over the tailpipe exhaust for the equipment being tested. A picture of the exhaust flow meter is provided in Figure 2.2 below. The exhaust flow rates are multiplied by the concentration levels for the various emission components to provide emission rates in grams per second.

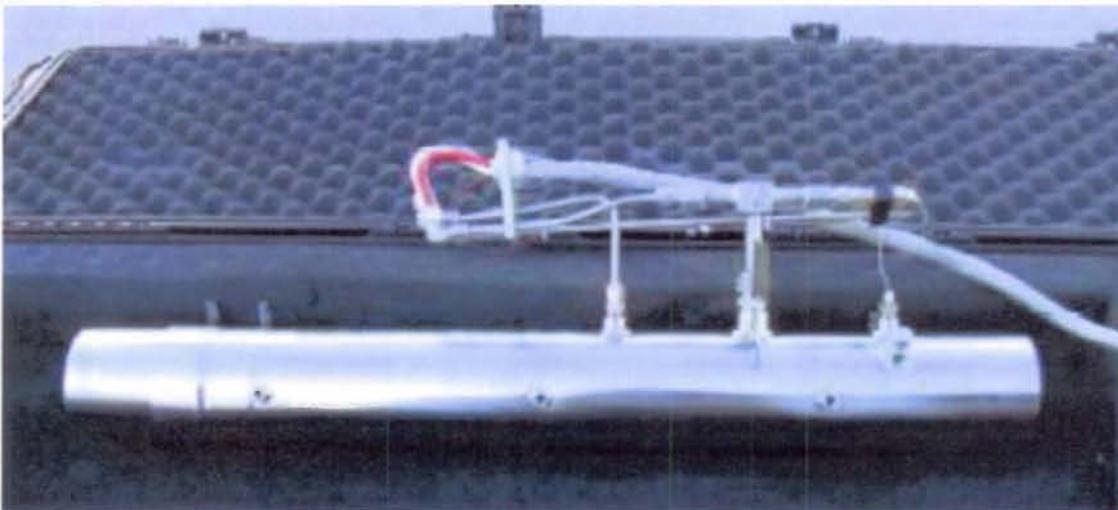


Figure 2-2: Picture of Semtech DS Exhaust Flow Meter

The second analyzer is a prototype AVL Micro Soot Sensor (MSS) with a gravimetric filter box. The MSS measures the soot concentration on a second by second basis by a photo-acoustic principle. The gravimetric filter box extends the soot measurement to a combination of time resolved soot and integral PM measurement based upon proprietary software. The stored data has to be post processed by the AVL Concerto software to determine PM emissions equivalent to the PM emissions determined by the traditional method of capturing the PM on a filter. A picture of the MSS and gravimetric filter unit is provided below.

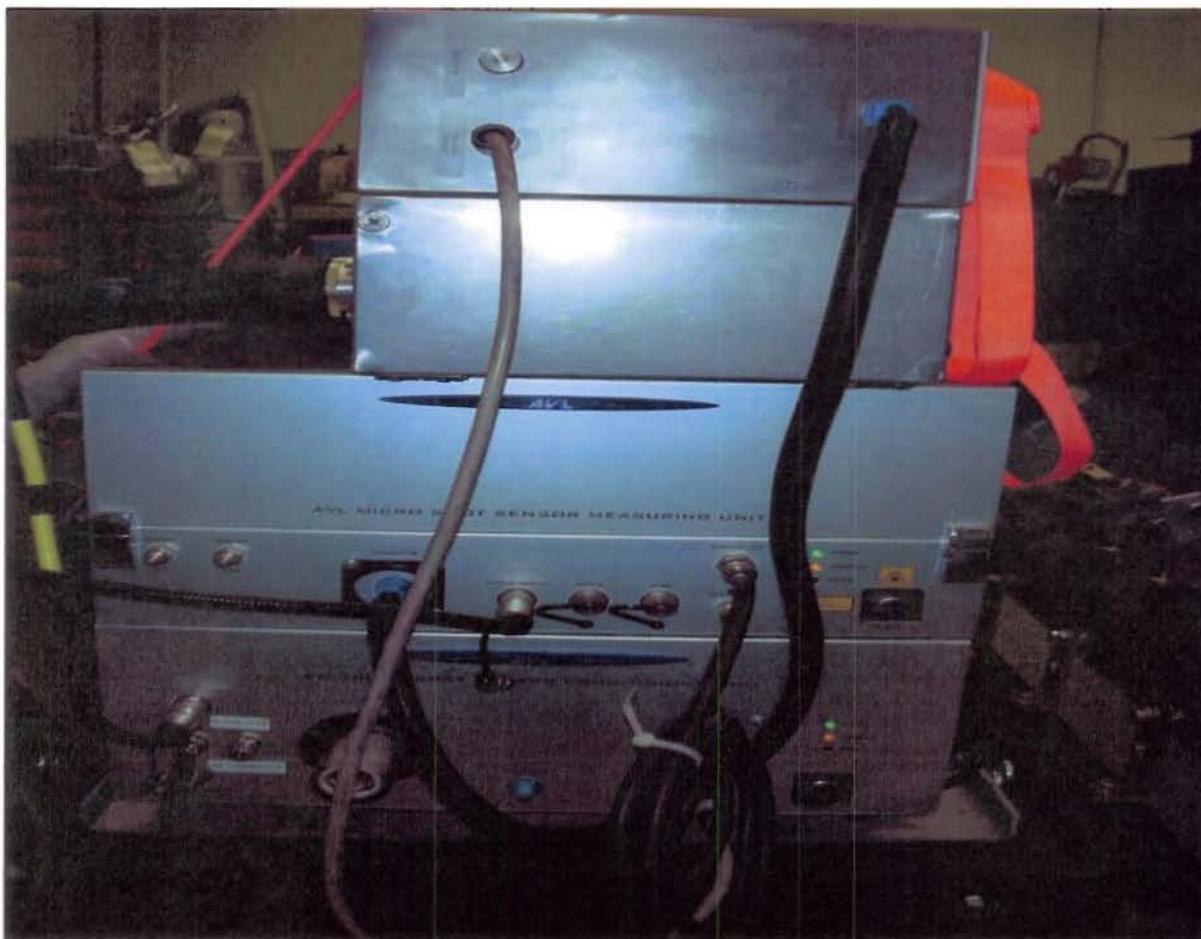


Figure 2-3: Picture of AVL Micro Soot Sensor with Gravimetric Filter Box on Top

Test Set-up

The test setup included the emissions analyzers (and associated exhaust flow meter), a gasoline powered Yamaha EF2800 generator to power the AC emission analyzers. The generator has a built in inverter to power DC equipment such as the PC for logging data. A picture of the generator is shown below.

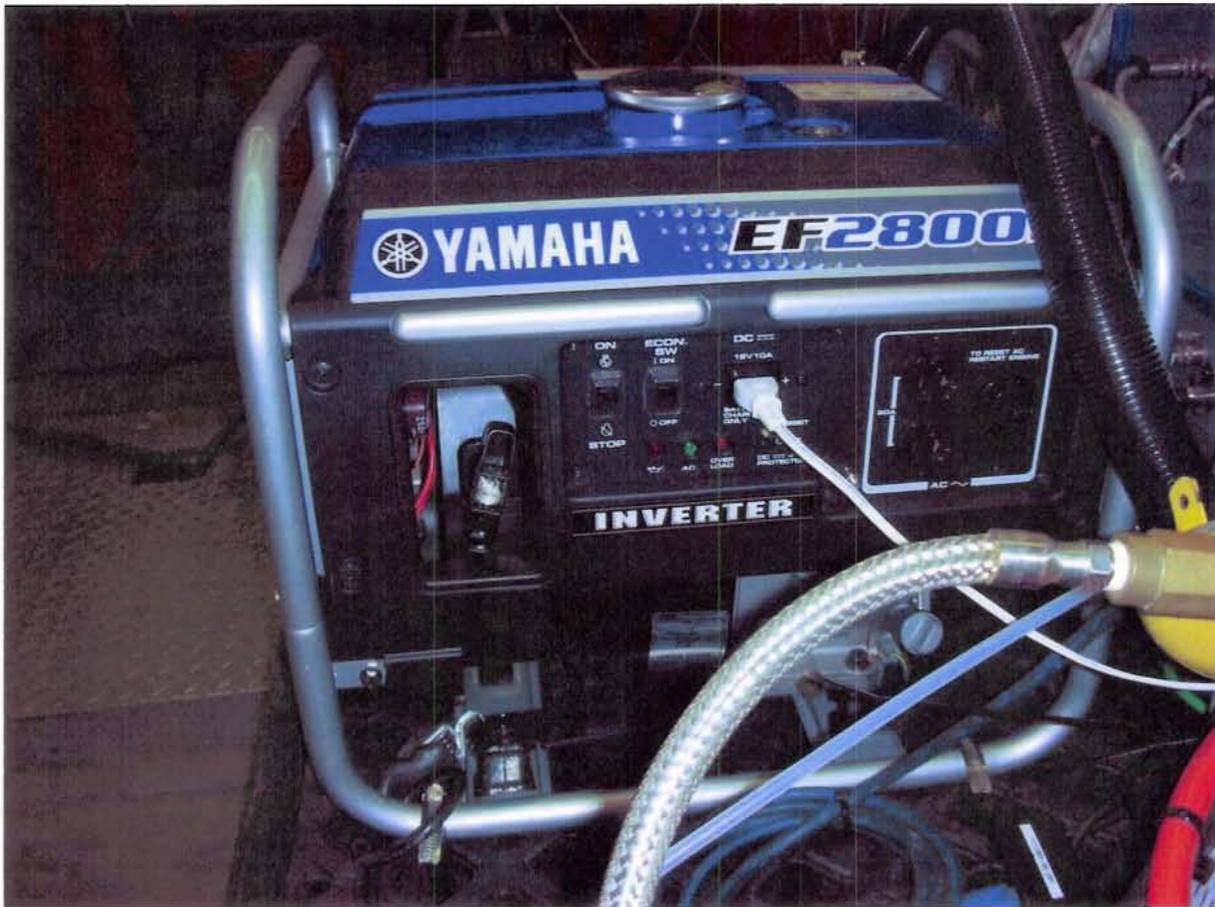


Figure 2-4: Yamaha EF2800 Generator for Powering Equipment

The emissions analyzers were housed in foam lined cases to provide protection from excessive vibration on the equipment. Initially the cases and generator were secured by straps to a 4 drum plastic pallet as shown in Figure 2-5 below. However, because of concerns expressed by the City of Riverside about placing a 4 foot by 4 foot pallet on the roof of their construction equipment the equipment was removed from the pallet and the pallet cut in half. All the emission measurement equipment was mounted on the 2 foot by 4 foot pallet and the generator gets mounted in a separate location on the construction equipment. Having the emission equipment securely fastened to the pallet and the pallet placed on a 6 inch thick foam and securely fastened to the construction equipment ensures the analyzers are stable over the course of a test day.



Figure 2-5: Emission Analyzers, Generator, and Flow Meter on a 4' by 4' Plastic Pallet

Preliminary Validation Testing¹

Previous studies at CE-CERT have validated the operation of the PEMS and provided cross comparisons of their operation with some of the other measurement techniques available at CE-CERT. For one such measurement, the analyzers were cross compared with the UC Riverside mobile emissions laboratory (MEL), which is a full dilution tunnel emissions system with laboratory grade analyzers on a mobile platform. MEL is a unique laboratory containing all of the instrumentation normally found in a conventional vehicle emissions laboratory, but the equipment is mounted inside a 53-foot over-the-road truck trailer, as shown in Figure 2-6. The laboratory contains a dilution tunnel, analyzers for gaseous emissions, and instrumentation for particulate measurements. The system is reconfigurable, and can measure real-time gaseous as well as particulate

¹ This section from: December 2008 Final Report to Caltrans, "Evaluating the Emissions from Heavy-Duty Construction Equipment", Matthew Barth, Thomas D. Durbin, J. Wayne Miller, and George Scora

matter (PM). Although much of the system is custom-designed, the laboratory was designed to conform to the Code of Federal Regulations (CFR) requirements for gaseous and particulate emissions measurements (CFR Parts 86 and 89). The laboratory is designed to operate as a class 8 tractor is pulling it over the road (or on a closed track over a repeatable cycle); it is not simply a roadside testing laboratory.

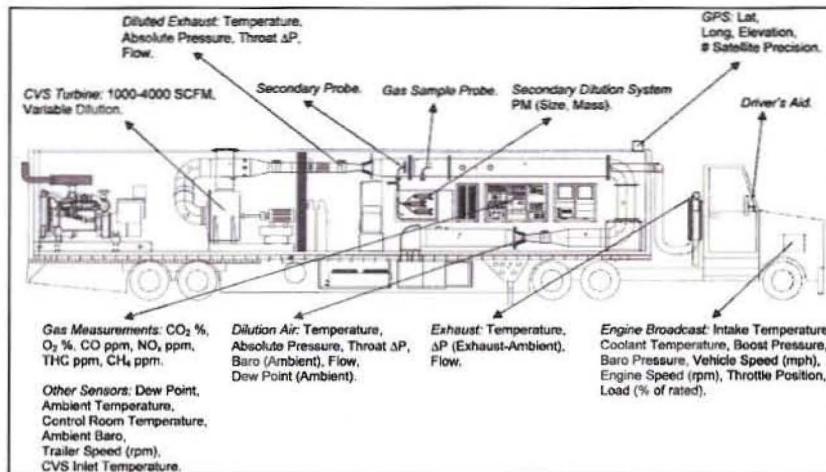


Figure 2-6: CE-CERT's Mobile Emissions Laboratory (MEL)

For these comparisons, the analyzers were positioned to measure raw exhaust concentrations upstream of the MEL dilution system. The MEL had been used for on-road validation of the PEMS measurement allowance for the PEMS in-use Not To Exceed (NTE) measurement regulatory program. The MEL measurements were made in the diluted exhaust and converted to equivalent raw exhaust concentrations by using the dilution ratio determined by the difference of the total tunnel flow minus the flow of the intake dilution air.

The comparisons of the PEMS and the MEL showed some differences in concentration levels, as shown in Table 2-1. The PEMS NO_x emission levels were biased 5-15% high relative to those of the MEL. This comparison for NO_x is in a similar range to that seen in previous comparisons between the MEL and PEMS. CO₂ measurements were all within 2%, except at the lowest load point. This is also consistent with previous comparisons and indicates good comparability for the CO₂ which is the basis for the fuel based comparisons. The deviations for CO and THC were higher than those for the other components. This is not surprising as CO and THC are generally found at relatively low levels in the diesel exhaust. Similar results have been found in other comparison studies.

Load point	Semtech Results (ppm)				MEL equivalent raw measurements (ppm)			
	NO _x	CO ₂	CO	THC	NO _x	CO ₂	CO	THC
100 %	1099.8	8.9	203.5	5.1	964.0	8.80	205.9	15.9
75 %	1112.0	7.92	135.4	NA	992.2	7.99	165.2	13.8
50 %	1004.0	6.88	125.0	24.4	919.9	7.01	143.9	20.1
25 %	640.8	5.23	98.84	42.7	595.2	5.30	88.3	27.0
10 %	344.3	3.56	119.5	76.4	325.4	3.82	127.7	42.4

Percentage differences (relative to MEL)

	NO _x	CO ₂	CO	THC
M100	14.1%	1.4%	-1.1%	-68.1%
M75	12.1%	-1.0%	-18.1%	NA
M50	9.1%	-1.9%	-13.1%	21.6%
M25	7.7%	-1.4%	11.9%	57.8%
M10	5.8%	-6.7%	-6.4%	80.3%

Table 2-1: Emissions concentration level comparison between PEMS and MEL

Construction Equipment Tested for Emissions

Five pieces of construction equipment (4 backhoes and 1 wheel loader) were rented from RDO Equipment Co. and operated on a vacant lot by CE-CERT personnel. Two wheel loaders operated by Riverside County personnel at a quarry in Thermal, California were also tested.

All of the tested equipment is listed in Table 2-2.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

Equipment Owner	Equipment Type	Location Tested	Model	Year	Tier	Engine Mfg	Engine Family	Engine Model	Equipment Mfg	Rated Power (HP)	Rated Speed (RPM)	Hrs	Hours tested
RDO	Backhoe	RDO Lot	410 J	2007	2	4045TT095	7JDXL04.5062	Deere	Deere	99	2200	1181.6	4
RDO	Backhoe	RDO Lot	310 SJ	2010	3	4045HT054	AJDXLO6.8106	Deere	Deere	99	2250	241.6	4
RDO	Wheel loader	RDO Lot	644 J	2007	3	6068HDW69	7JDXL06.8101	Deere	Deere	225	2200	1735	4
RDO	Backhoe	RDO Lot	310 SG	2006	2	4045TT089	6JDXL04.5062	Deere	Deere	92	2300	2599	4
RDO	Backhoe	RDO Lot	410 G	2006	2	4045TT093	6JDXL04.5062	Deere	Deere	99	2200	945.9	4
County of Riv	Wheel loader	Riverside County quarry	WA470-6	2009	3	SAA6D125E-5	9KLXL11.0DD6	Komatsu	Komatsu	273	2000	900	3
County of Riv	Wheel loader	Riverside County quarry	CAT 928G	2004	2	CAT		C6.6	CAT	120	2300	2294	3

Table 2-2: Equipment Tested

Pictures of the equipment with the emission measurement analyzers in place are presented in Figures 2-7 through 2-13.



Figure 7: John Deere Backhoe 410J on Vacant Lot in Riverside, California



Figure 2-8: John Deere Backhoe 310SJ on Vacant Lot in Riverside, California



Figure 2-9: John Deere Wheel Loader 644J on Vacant Lot in Riverside, California



Figure 2-10: John Deere Backhoe 310SG on Vacant Lot in Riverside, California



Figure 2-11: John Deere Backhoe 410G on Vacant Lot in Riverside, California



Figure 2-12: Komatsu WA470-6 Wheel Loader at Quarry in Thermal, California



Figure 2-13: Caterpillar 928G Wheel Loader at Quarry in Thermal, California

3.0 Results

The results are shown in Figure 3-1 through Figure 3-7. In these figures the first plot is the fuel rate in g/sec followed by plots of CO₂, CO, THC, and NO_x, in g/kg fuel on the left axis (black line) and in g/sec on the right axis (green line). The last plot in the series is PM in mg/m³. These plots are based on the data as recorded without time aligning the emission data to the flow rate data.

The PM concentration data in mg/m³ was converted to a PM mass emission rate in g/sec according to equation 3.1 and is presented in Figure 3-8 through Figure 3-17. The PM in mg/m³ is strictly a measure of the soot (black carbon) concentration in the exhaust whereas the typical filter measurement of PM includes not only soot but also heavy organic compounds. To account for these contributions, equation 3.1 applies an adjustment factor of 1.2 to the soot based PM value. The factor of

$$PM_m = (PM_c \times Flow \times 0.47195 \times 1e - 6) \times 1.2 \quad (3.1)$$

where

$$\begin{aligned} PM_m &= PM \text{ total mass emission (g/s)} \\ PM_c &= dilution corrected PM soot concentration (mg/m^3) \\ Flow &= Exhaust flow rate in SCFM \end{aligned}$$

1.2 is based upon data from an onroad diesel engine² in which it was observed that this was a consistent ratio between PM_m and soot emissions in g/s from the AVL Concerto program.

Calculation of the PM mass emission rate is dependent on PM concentration data from the AVL Micro Soot Sensor, exhaust flow rate data from the Semtech DS flow meter, and proper alignment between the two data sets. Time alignment between the two data sets was performed manually by aligning key events in the PM concentration and CO₂ values as seen in Figure 3-18 and Figure 3-19. Figure 3-18 shows an example of the alignment of the general modes of activity across the test data set while Figure 3-19 shows the alignment of spikes at the second-by-second scale for a smaller portion of the data set.

² Final Report, "Validation Testing for the PM-PEMS Measurement Allowance Program", Contract No. 07-620, Prepared for : Dipak Bishnu, CARB, November 2010, by Kent Johnson, Tom Durbin, Heejung Jung, David R. Cocker, Mohammad Yusuf Khan

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

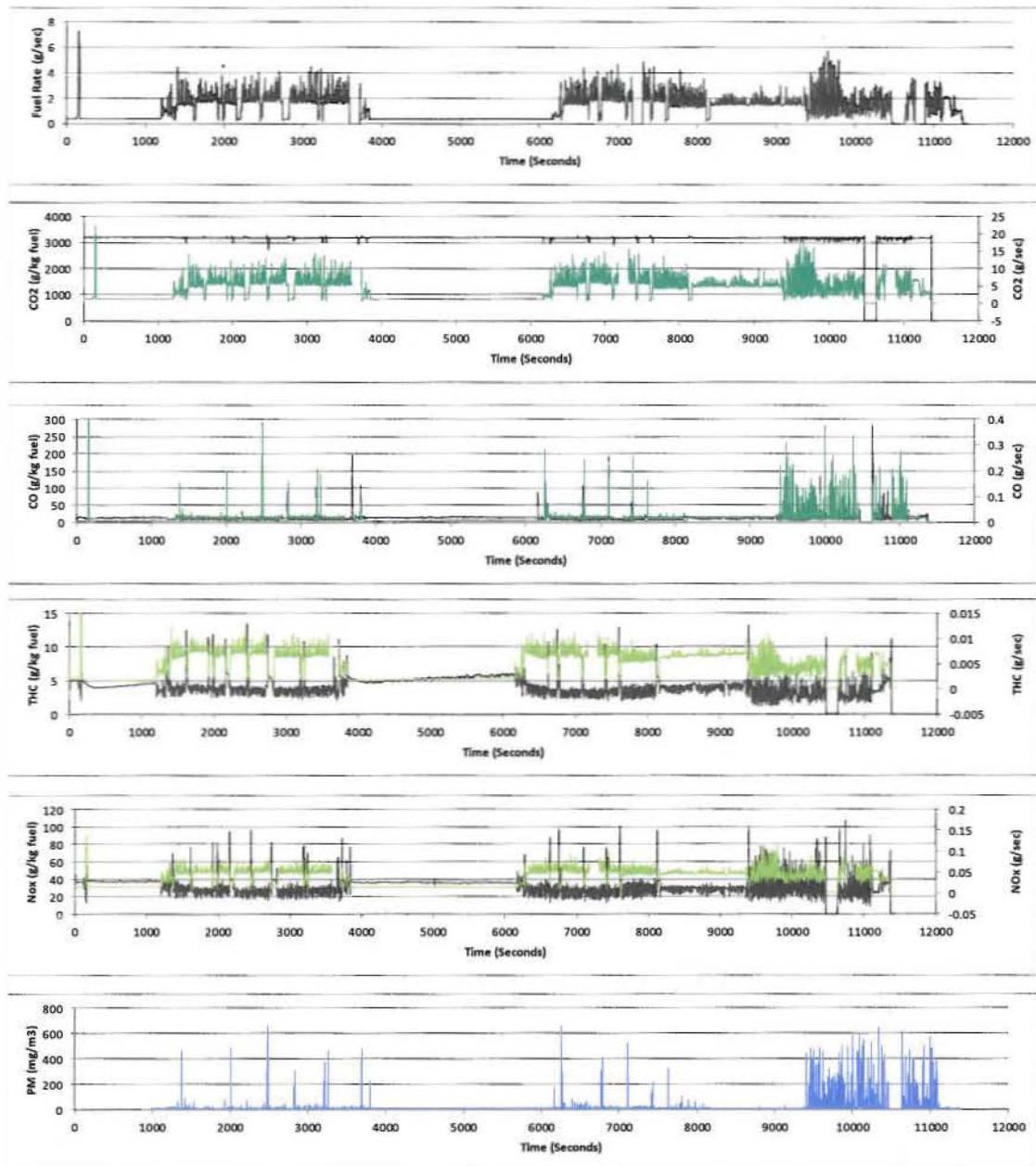


Figure 3-1: Emissions from John Deere 410J Backhoe on 12/03/2010

Black lines are emissions in g/kg fuel, green lines are emissions in g/sec.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

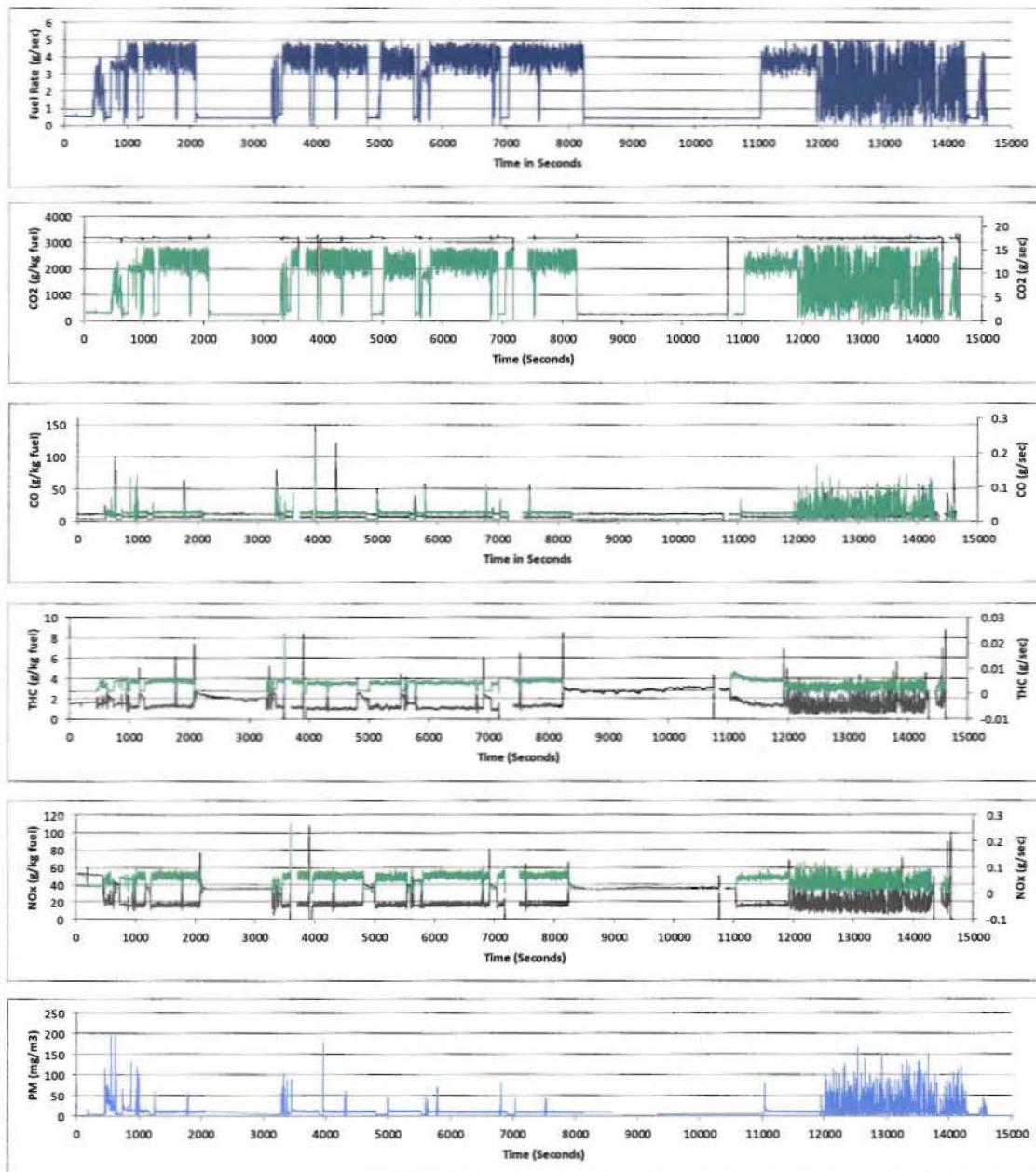


Figure 3-2: Emissions from John Deere 310SJ Backhoe on 12/07/2010

Black lines are emissions in g/kg fuel, green lines are emissions in g/sec.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

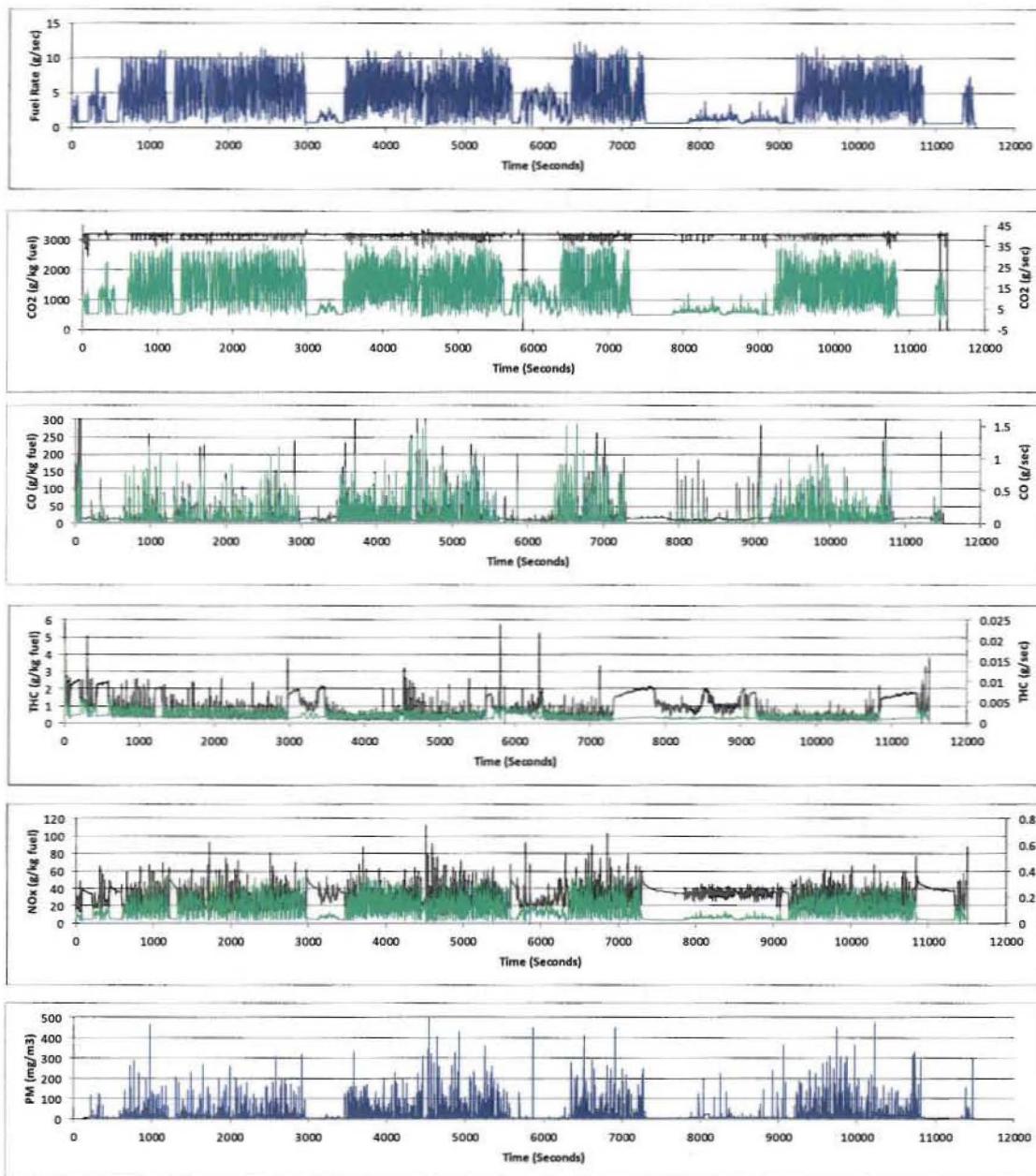


Figure 3-3: Emissions from John Deere 644J Wheel Loader on 12/08/2010

Black lines are emissions in g/kg fuel, green lines are emissions in g/sec.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

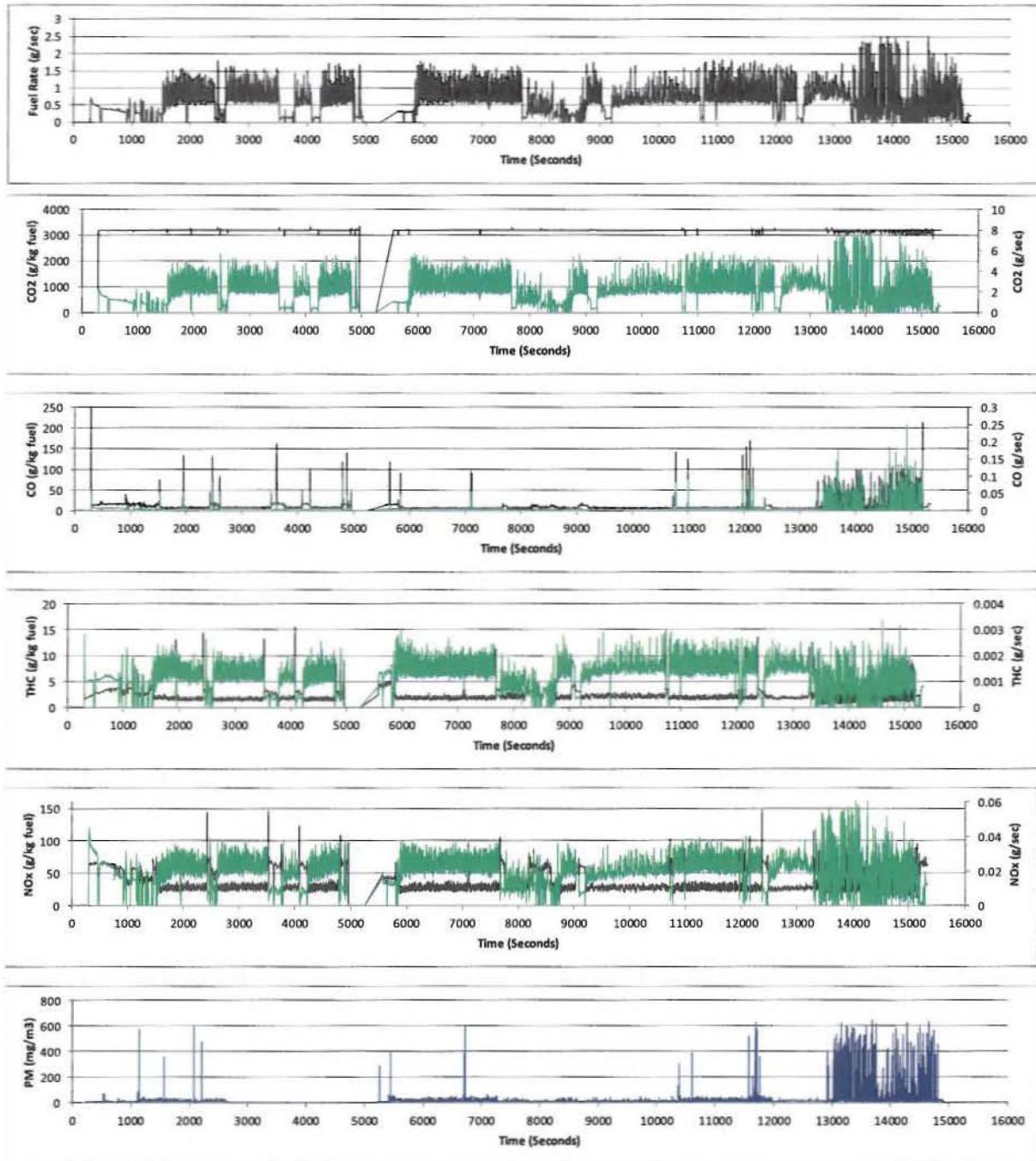


Figure 3-4: Emissions from John Deere 310SG Backhoe on 12/09/2010

Black lines are emissions in g/kg fuel, green lines are emissions in g/sec.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

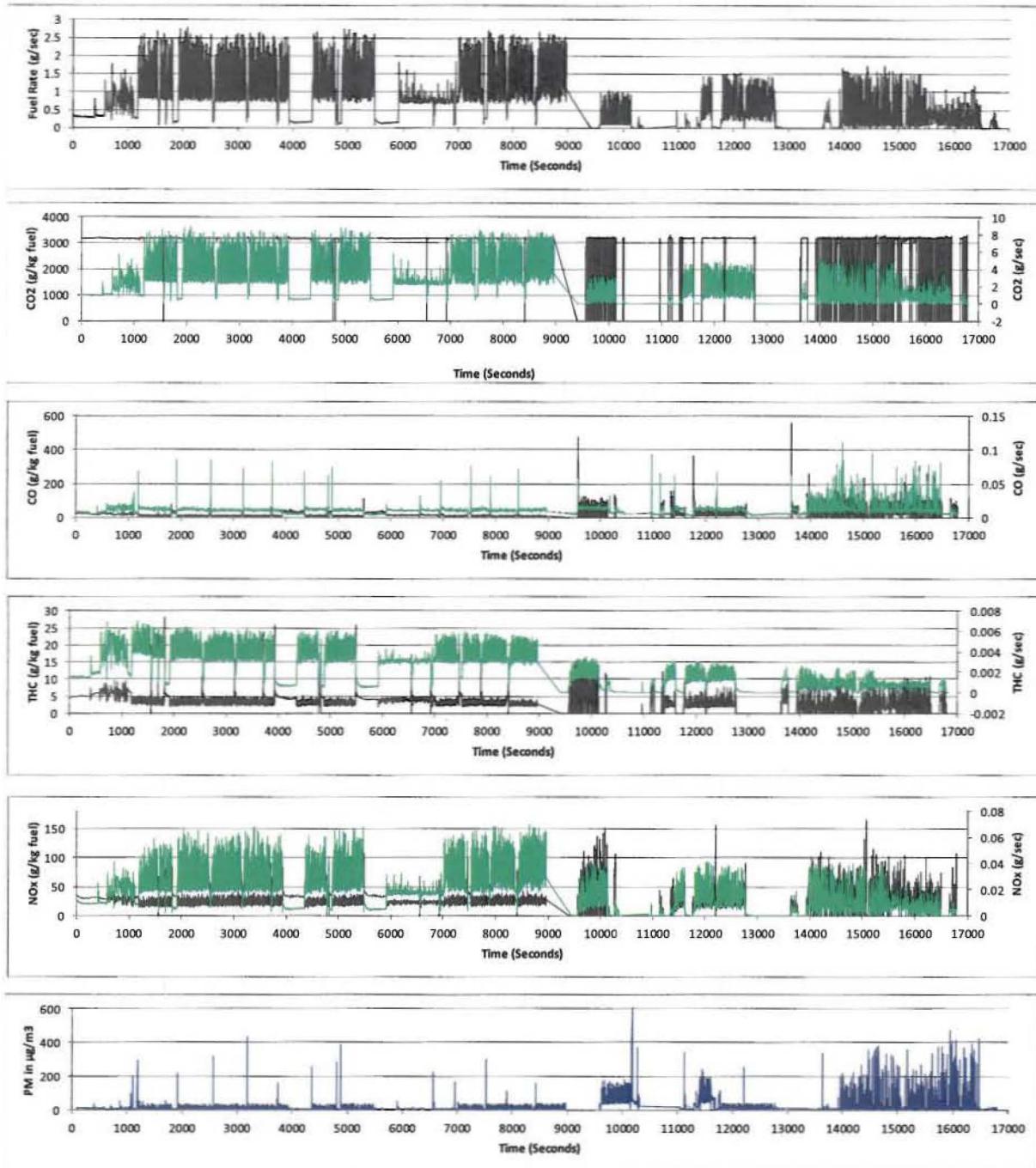


Figure 3-5: Emissions from John Deere 410G Backhoe on 12/10/2010

Black lines are emissions in g/kg fuel, green lines are emissions in g/sec.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

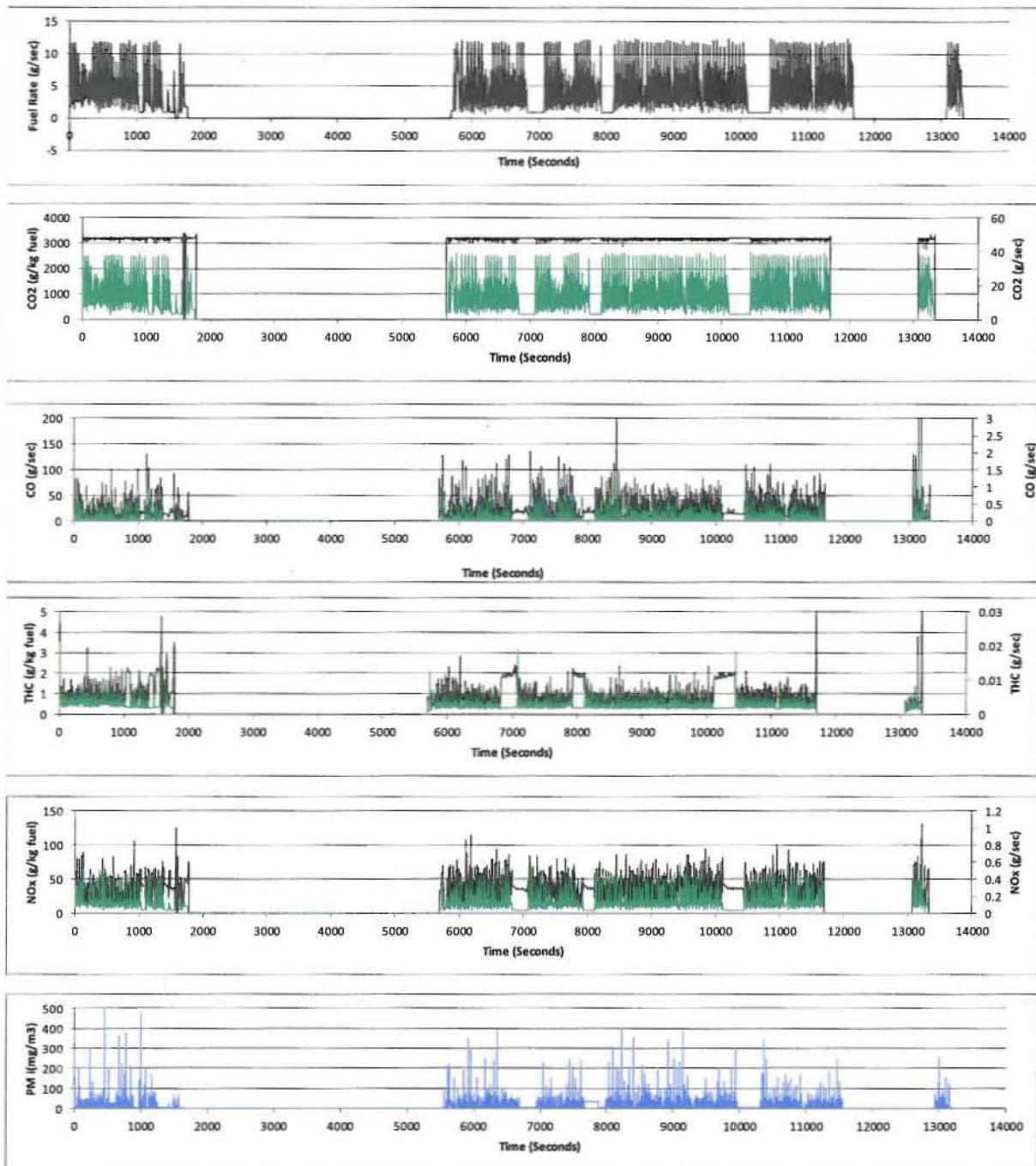


Figure 3-6: Emissions from Komatsu WA470-6 Wheel Loader on 2/09/2011
Black lines are emissions in g/kg fuel, green lines are emissions in g/sec.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

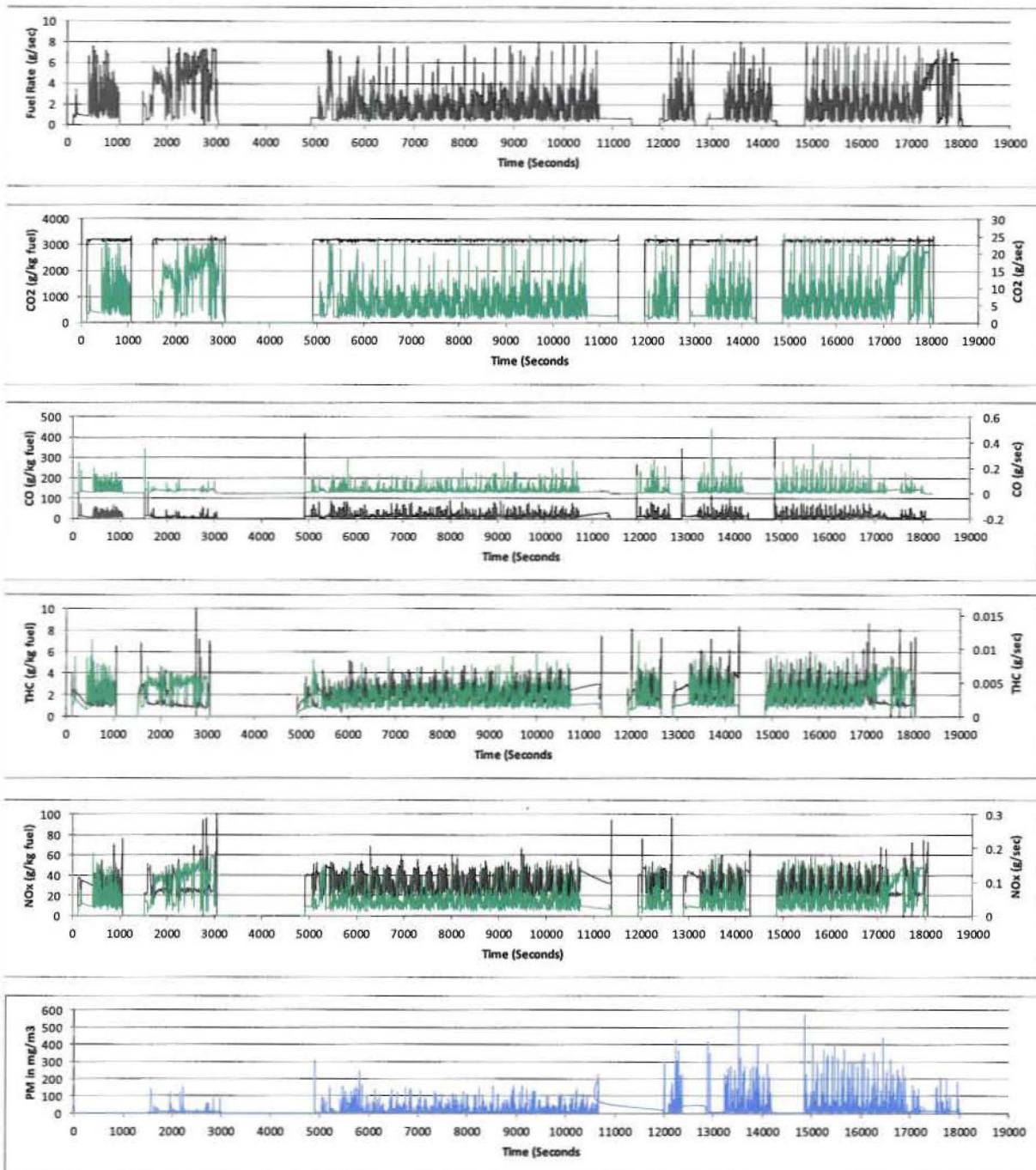


Figure 3-7: Emissions from Caterpillar 928G Wheel Loader on 2/10/2011

Black lines are emissions in g/kg fuel, green lines are emissions in g/sec.

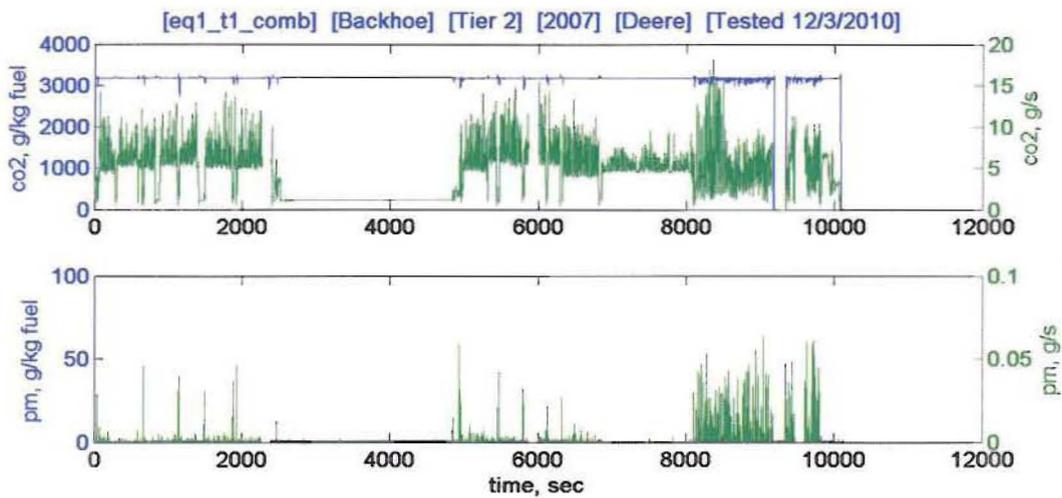


Figure 3-8: CO₂ and PM emissions from a 2007 Tier 2 John Deere 410 J backhoe.

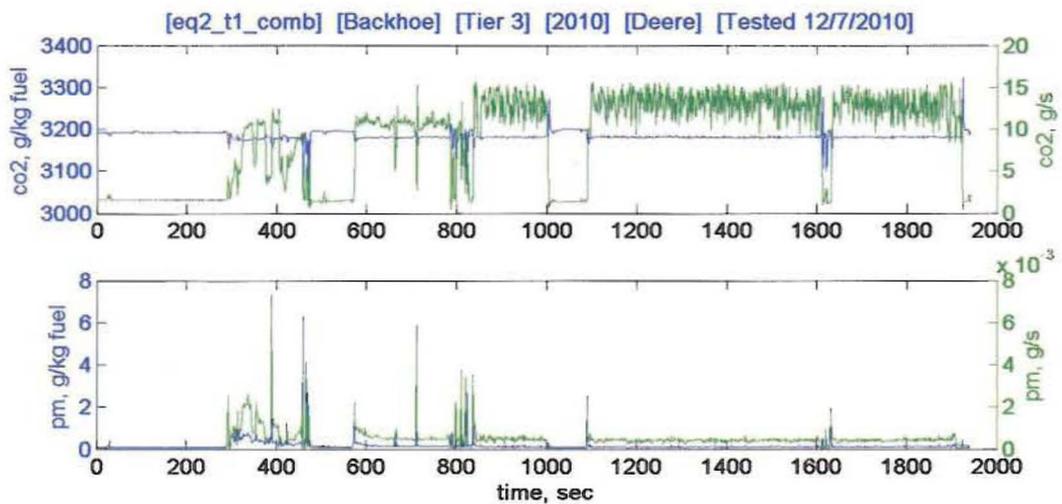


Figure 3-9: CO₂ and PM emissions from a 2010 Tier 3 John Deere 310 SJ backhoe.

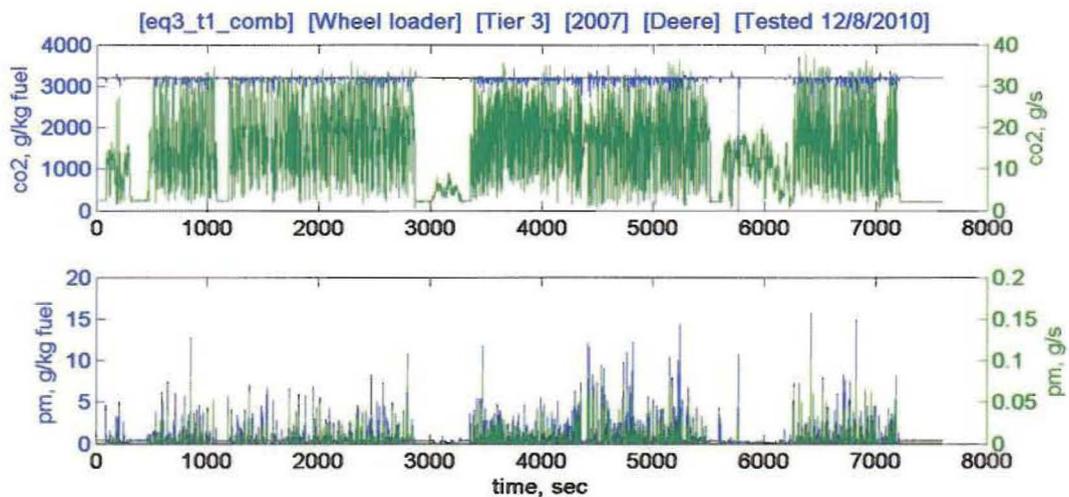


Figure 3-10: CO₂ and PM emissions from a 2007 Tier 3 John Deere 644 J wheel loader.

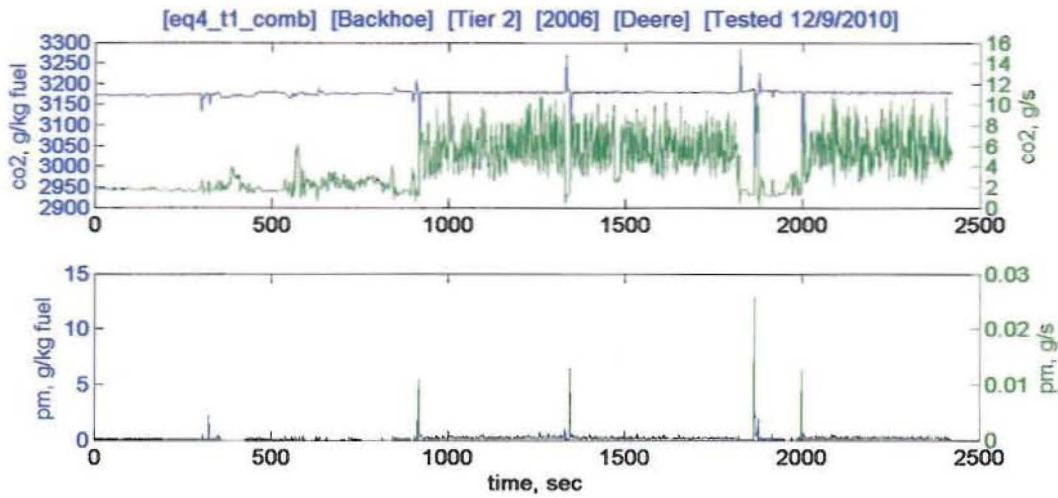


Figure 3-11: CO₂ and PM emissions from a 2006 Tier 2 John Deere 310 SG backhoe for 1st test.

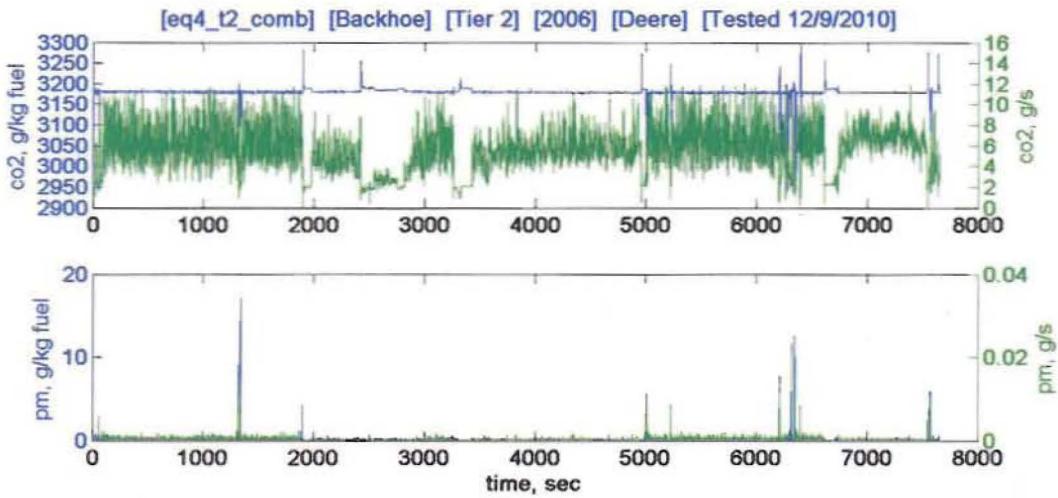


Figure 3-12: CO₂ and PM emissions from a 2006 Tier 2 John Deere 310 SG backhoe for 2nd test.

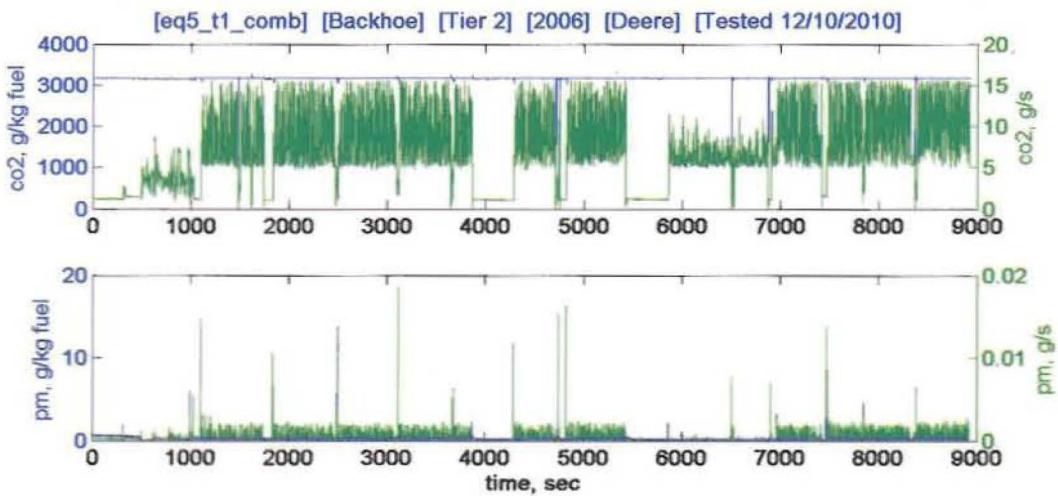


Figure 3-13: CO₂ and PM emissions from a 2006 Tier 2 John Deere 410 G backhoe.

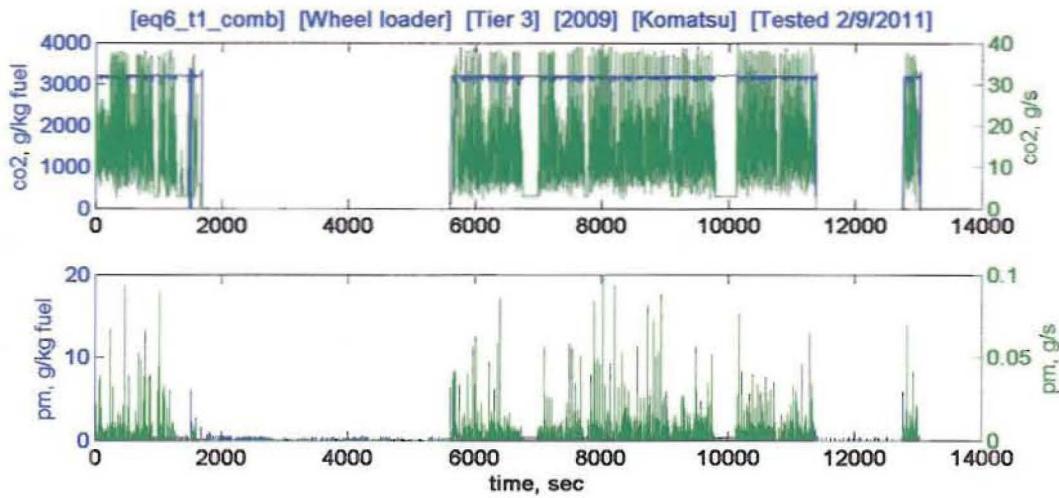


Figure 3-14: CO₂ and PM emissions from a 2009 Tier 3 Komatsu WA470-6 wheel loader.

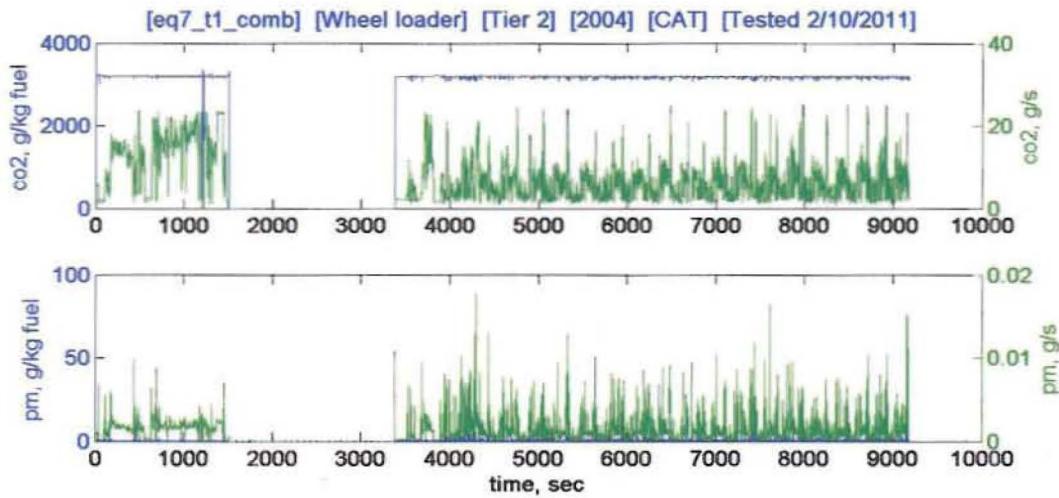


Figure 3-15: CO₂ and PM emissions from a 2004 CAT 928G backhoe for 1st test.

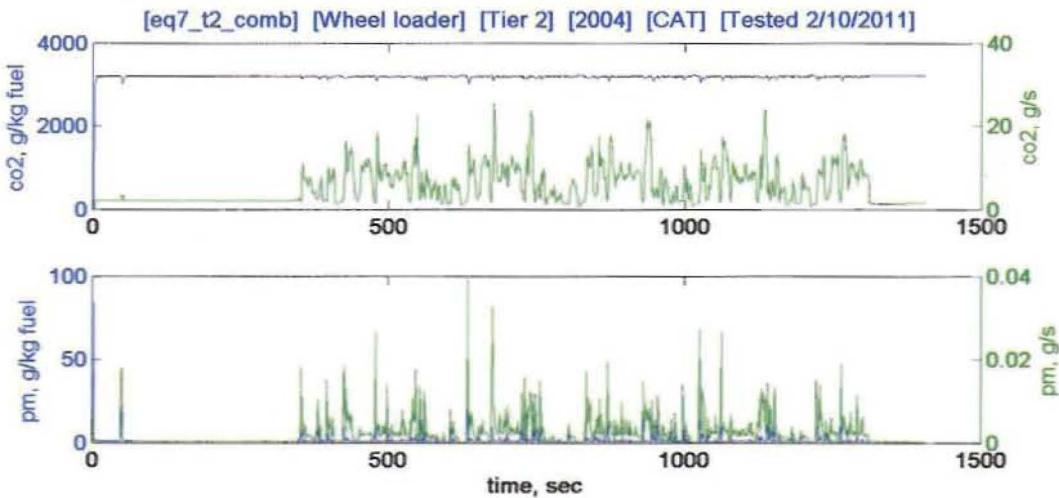


Figure 3-16: CO₂ and PM emissions from 2004 CAT 928G wheel loader for 2nd test.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

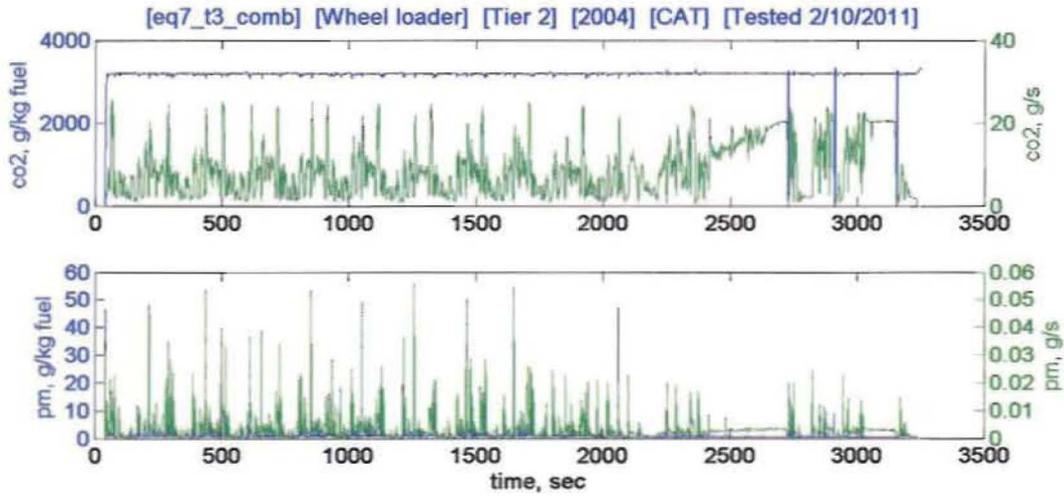


Figure 3-17: CO₂ and PM emissions from 2004 CAT 928G wheel loader for 3rd test.

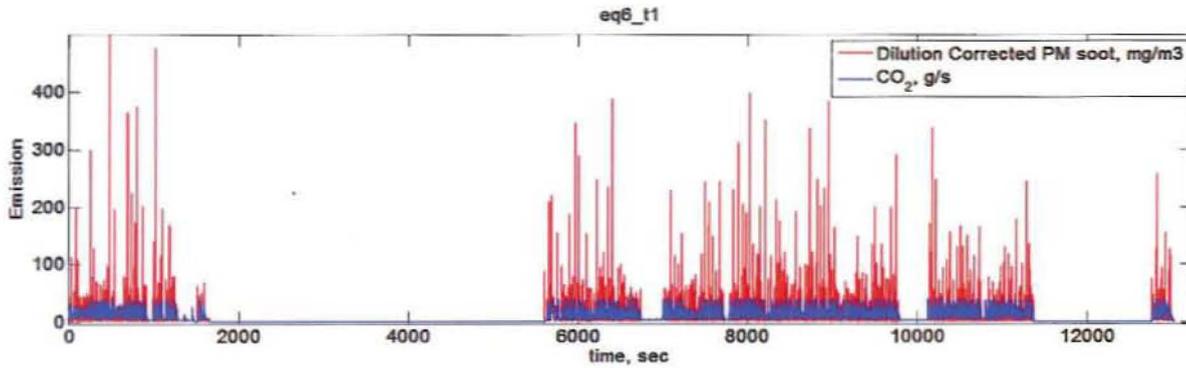


Figure 3-18: Time alignment example showing pattern of emission events across one test.

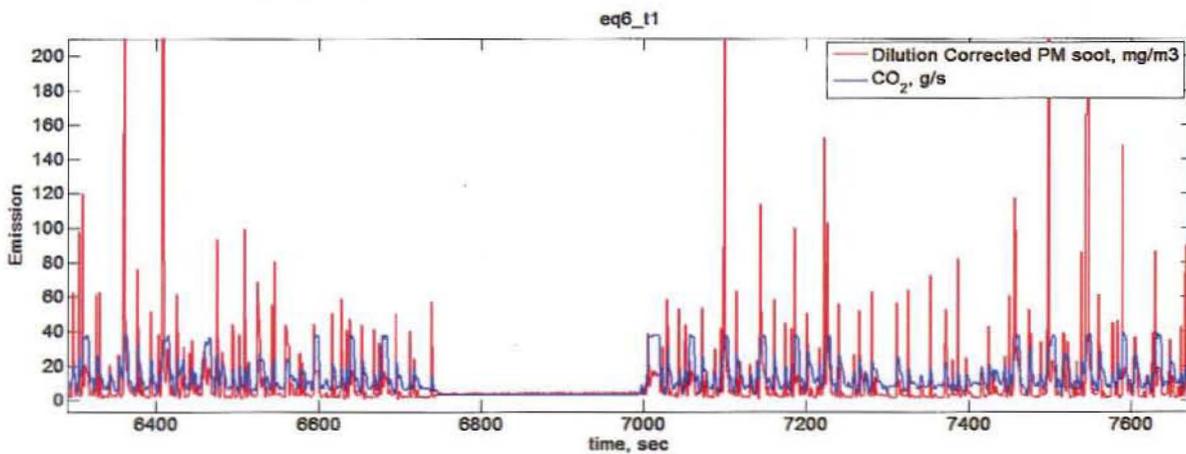


Figure 3-19: Time alignment example showing alignment of emission spikes at a smaller scale.

4.0 Off Road Equipment Emission Estimator (ORE)

One of the primary objectives of this research project is to create an emission model to better represent emissions produced in the field from heavy duty diesel construction vehicles. The test procedure and data collection was presented in previous sections. In this section, a description of the data analysis, emission modeling methodology and Graphical User Interface (GUI) are provided.

Data Analysis

Emission data from this study were analyzed for modeling purposes. The context of the analysis was to determine what data could be used for modeling and how. One of the primary concerns for modeling off-road equipment is determining the load on the vehicle. Vehicle load is dependent on activity. The activity data was mapped in Google Earth and examples are presented in Figures 4-1 and 4-2. In these figures the green star indicates the start location of the activity and the red star indicates the end location of the activity. These figures give some information about the type of activity which occurred during testing such as movement from a starting location to a work area and movement within a working area. This information is not sufficient to determine the load on a vehicle however.

Another indicator of activity can be determined from the engine test data. This data is presented in Figures 4-3 and 4-4, includes fuel use rate, engine speed and vehicle forward velocity. The vehicle forward velocity is estimated from the GPS data. In these two examples, it is clear that vehicle activity varies and that there are at least two distinct operating modes: idle and non-idle. These two modes can be differentiated largely by engine speed (rpm), but also from the profile of the fuel use or CO₂ emission rate. An example of data split into these two modes is presented in Figure 4-5. The blue points, which are a very minor fraction of the data, were not included in the model because it is difficult to classify them absolutely as either idle or work. Vehicle velocity is not a good indicator of idle activity since the equipment can be under load in a stationary or relatively stationary position which is evident in Figure 4-3.

Examples of emission rate data for two test files are presented in Figures 4-6 and 4-7. In these figures the emission rate is presented based on fuel use and time. The fuel based emission rate is indicated by the blue and the time based emission rate is indicated by green. The examples in these figures show the variance of fuel based and time based emission rates throughout the length of a test. In the second subplot, in Figures 4-6 and 4-7, the emission rate for CO₂ is presented. The fuel specific emission rate for CO₂ is fairly constant while the engine is on, as would be expected since almost all of the carbon in fuel is oxidized to CO₂ during the combustion process. This direct relationship does not exist between fuel and CO, HC or NO_x, depicted in the following subplots in Figures 4-6 and 4-7. Trends for these emission rates vary throughout the length of the test. Comparing the fuel rate in the first subplot to emissions in the following subplots in Figures 4-6 and 4-7, shows that fuel specific emission rates for CO, HC and NO_x increase at low fuel rates. This trend is particularly noticeable during

idle which is characterized by a higher fuel specific CO, HC and NO_x emission rate than under steady load.

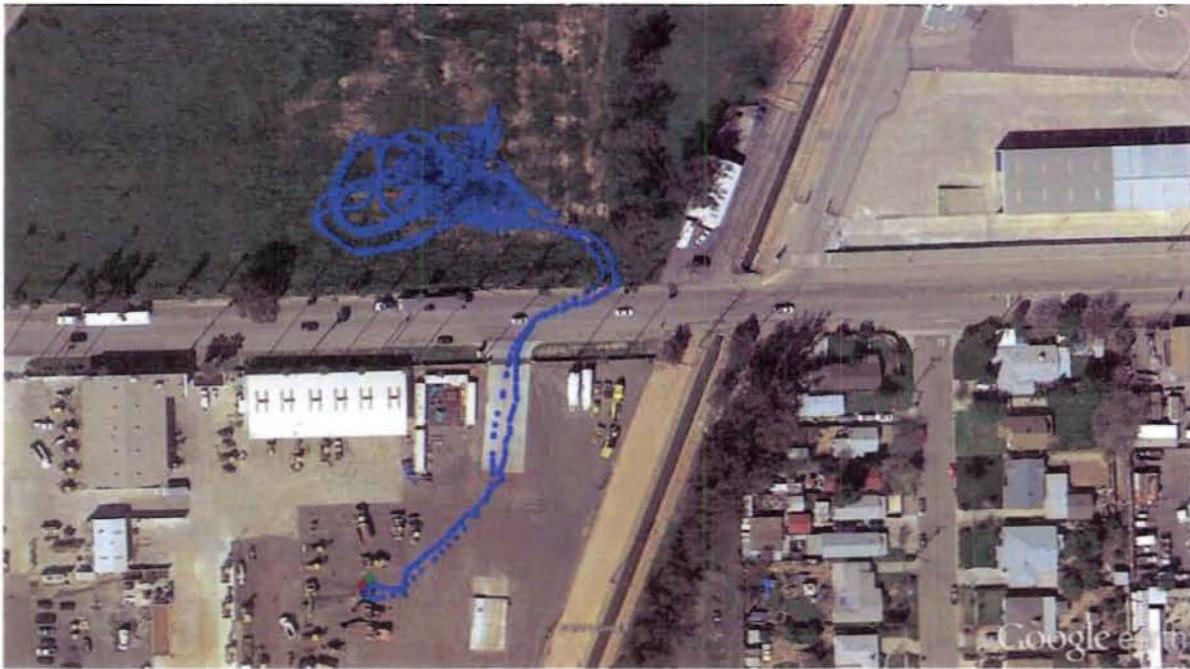


Figure 4-1: This figure shows sample mapped activity data for a back hoe. The green star is the starting location and the red star is the ending location.



Figure 4-2: This figure shows sample mapped activity data for a wheel loader. The green star is the starting location and the red star is the ending location.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

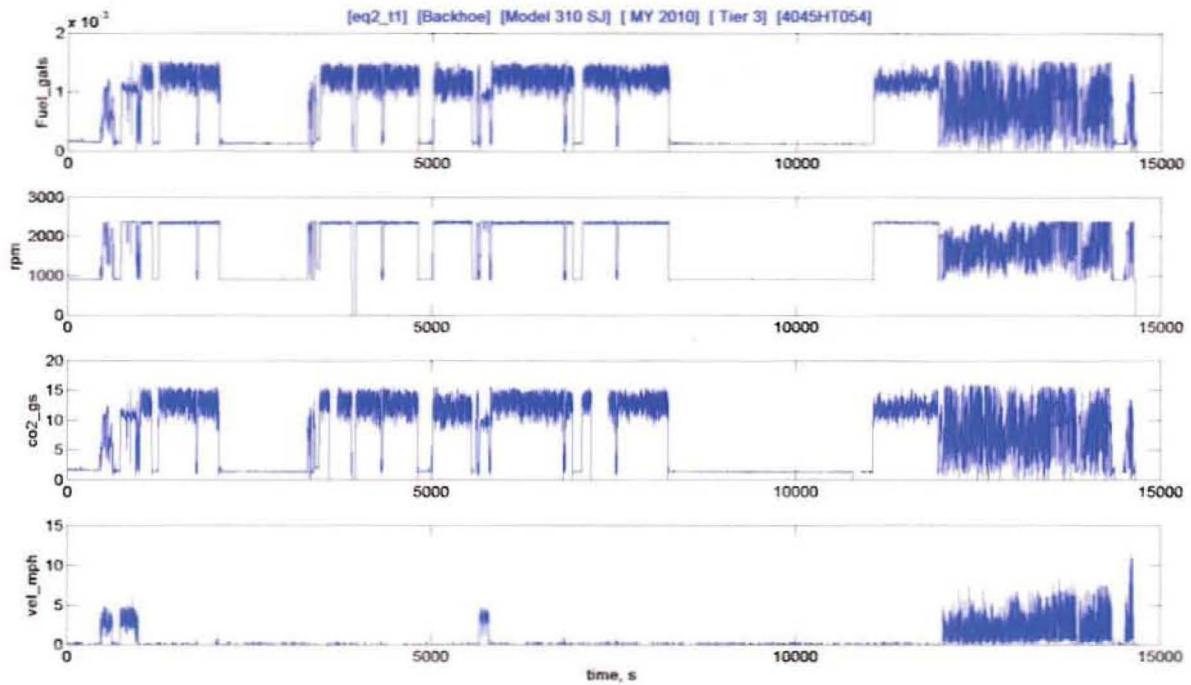


Figure 4-3: This figure shows sample activity data for a Backhoe.

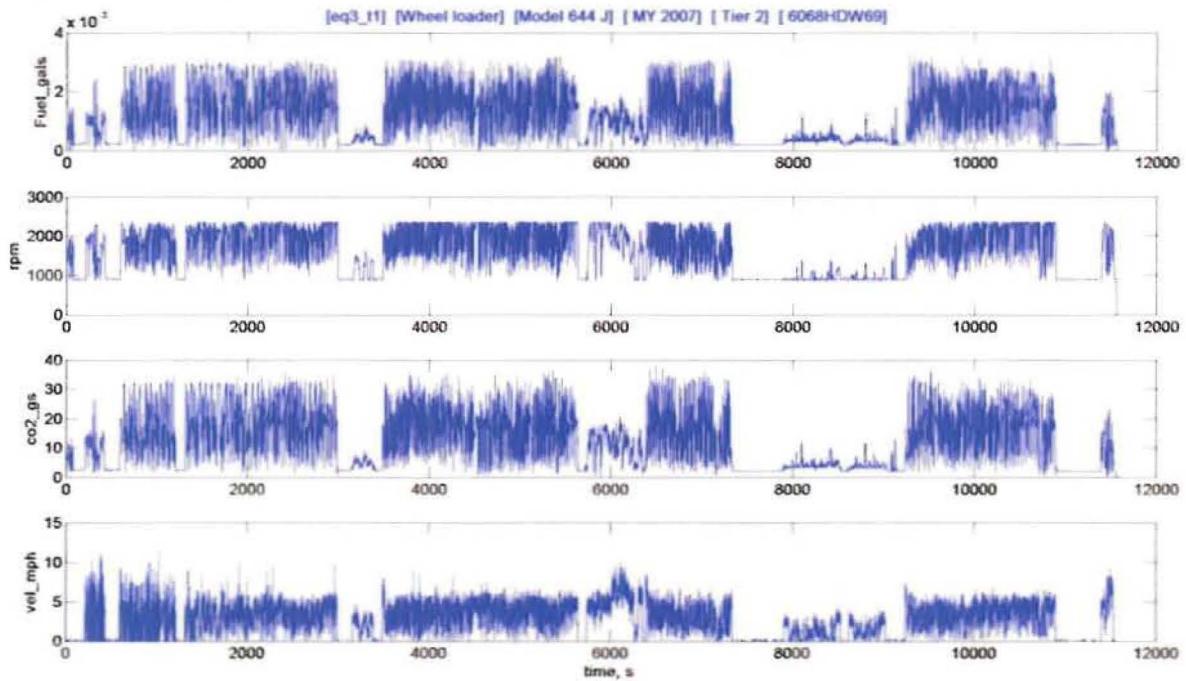


Figure 4-4: This figure shows sample activity data for a wheel loader.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment

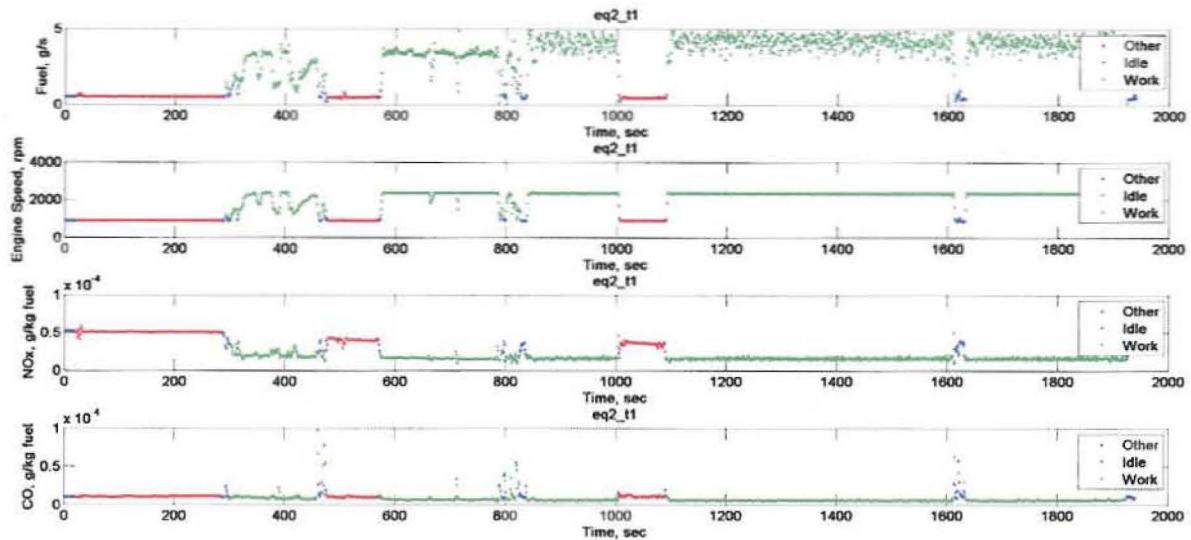


Figure 4-5: This figure shows an example of the separation of the data ranges into idle and work modes. Data colored red is in the idle mode while data colored green is in the work mode. Blue colored data is not incorporated in emission factor calculations.

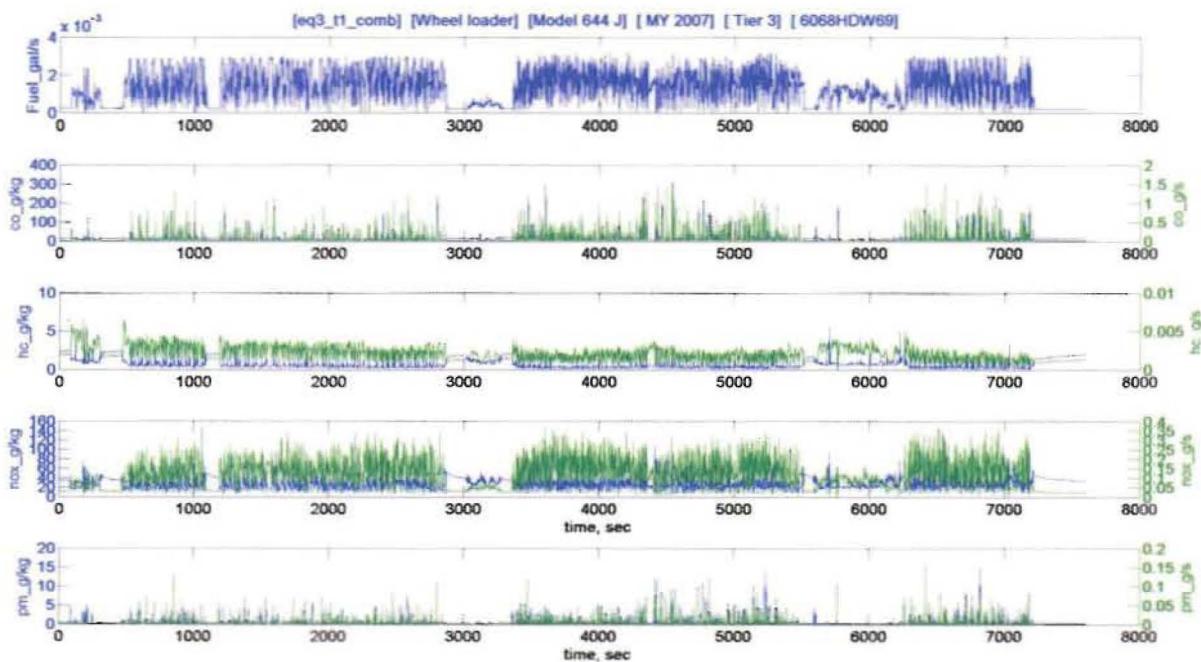


Figure 4-6: This figure shows sample emission rate data for a wheel loader.

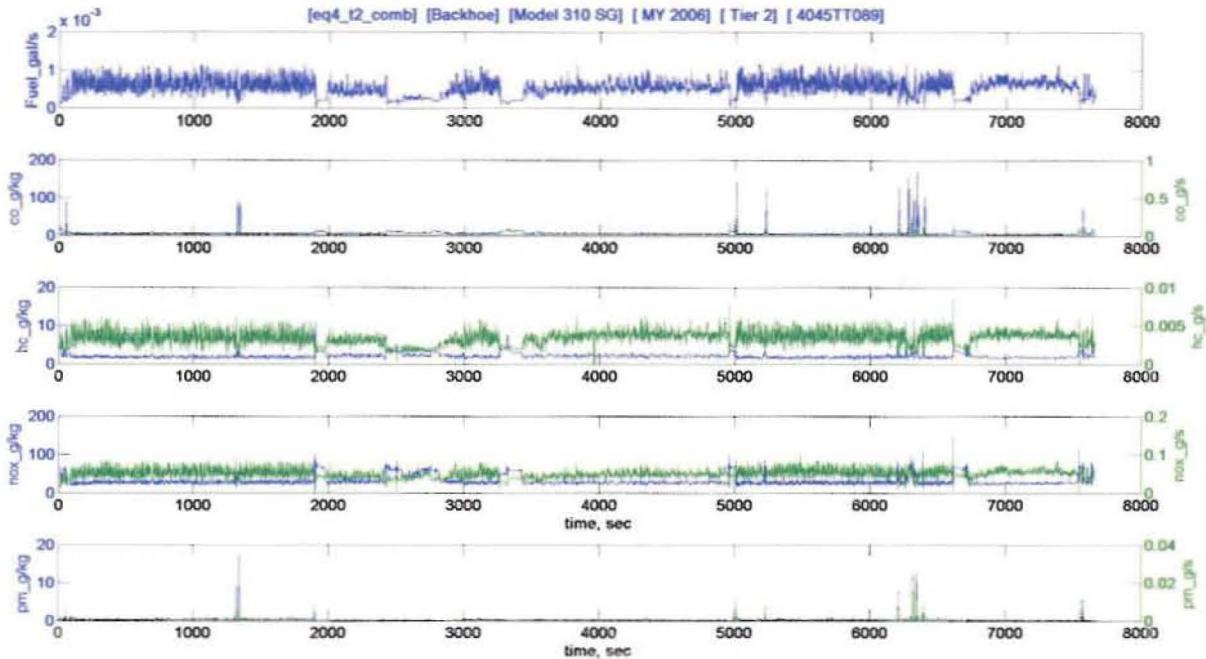


Figure 4-7: This figure shows sample emission rate data for a Backhoe.

ORE Modeling Methodology

One constraint in any modeling process is always the availability of the input data. A model that requires inputs which are not readily available is not useful. The model developed here is based on fuel consumed, fraction of time spent in each mode and fuel based emission factors. This methodology was established in earlier work which utilized only emission data in units of concentration. The advantage of this method is that emission factors can be calculated from concentration data and that emission predictions are easily derived from inputs of fuel consumed. The data analysis in the previous section demonstrates that fuel specific emissions are generally higher at idle and decrease under load. The proposed framework for a construction model based on the test data collected would consist of two sets of fuel based emission factors, one for idle mode and one for load conditions.

Fuel based emissions are calculated from either concentration data or mass emission rates. The basic calculation based on concentration data is illustrated in equation 4.1. The fuel rate is estimated based on a carbon balance with emissions. The terms for CO and HC in the denominator may be excluded since roughly 99% of the carbon in fuel is oxidized to CO₂ and relatively little ends up in CO and HC.

$$\frac{emission, g}{fuel\ use, g} = \frac{emission \times \rho_{emission} \times CWF_{fuel}}{(CO_2 \times \rho_{CO_2} \times CWF_{CO_2} + CO \times \rho_{CO} \times CWF_{CO} + HC \times \rho_{HC} \times CWF_{HC})} \quad (4.1)$$

where

- $emission$ = the emission rate in ppm
- $\rho_{emission}$ = the emission density in g/l
- CO_2 = CO_2 emission rate in ppm
- CO = CO emission rate in ppm
- HC = HC emission rate in ppm
- ρ_x = the density of x in g/l, (x = CO_2 , CO, HC, NO_x , PM)
- CWF_x = the carbon weight fraction of x, (x = Fuel, CO_2 , CO, HC)

When mass emission rates are provided, the fuel based emission factor can be calculated easily by equation 4.2.

$$\frac{emission, g}{fuel\ use, kg} = \frac{emission, g/s}{fuel, g/s} \times 1000 \quad (4.2)$$

Fuel based emission rate factors are applied to fuel use to estimate a mass emission rate as shown in equation 4.3.

$$emission, g = \left[\frac{emission, g}{fuel\ use, kg} \right] \times fuel\ use, kg \quad (4.3)$$

where

$$\left[\frac{emission, g}{fuel\ use, kg} \right] = \text{a fuel based mass emission factor}$$

Four equipment categories were created from the collected data set and they are presented in Table 4-1. The 4 categories consist of a Tier 2 and Tier 3 wheel loader and

Equipment Category	Equip. ID	Date Tested	Equip. Type	Tier	Year	Engine Manufacturer/Engine Model	Model	Disp.	Cylinders	Rated Power	Hours Tested
	#							l	#	hp	Hrs
Backhoe Tier 2	1	12/3/2010	Backhoe	2	2007	Deere/4045T1095	410 J	4.5	4	99	4
	4	12/9/2010	Backhoe	2	2006	Deere/4045T1089	310 SG	4.5	4	92	4
	5	12/10/2010	Backhoe	2	2006	Deere/4045T1093	410 G	4.5	4	99	4
Backhoe Tier 3	2	12/7/2010	Backhoe	3	2010	Deere/4045HT1054	310 SJ	6.8	6	99	4
Wheel Loader Tier 2	7	2/10/2011	Wheel loader	2	2004	Cat/C6.6	CAT 928G	6.6	6	120	3
Wheel Loader Tier 3	3	12/8/2010	Wheel loader	3	2007	Deere/6068HDW69	644 J	6.8	6	225	4
	6	2/9/2011	Wheel loader	3	2009	Komatsu/SAA6D125SE-5	WA470-6	11.04	6	273	3

Table 4-1: Description of Equipment Tested

a Tier 2 and Tier 3 backhoe. Each of these categories was developed based on 3 to 12 hours of test data and 1 to 3 test vehicles.

From the data analysis presented in the previous section, the idle and load mode were determined to be distinct in a number of tests for most emission species tested and for several construction vehicles. Table 4-2 presents emission factors for these two modes of operation for the 4 equipment categories. These emission factors reflect the total construction vehicle activity that occurred during the test period for all pieces of equipment within a test group. Assuming that the machinery tested during this test period was operated in a typical fashion, these emission factors would be representative of typical emission factors for these construction vehicle categories. Typically one expects that all the emission factors for a Tier 3 will be lower than for a Tier 2. This holds true for the Tier 3 backhoes versus the Tier 2 backhoes. For the Tier 3 wheel loaders the Tier 3 emission factors for CO are higher than the Tier 2 by 21% for idling and 73% for working, and the Tier 3 NO_x working emission factor is higher than the Tier 2 by 15%. Since CO is so far below the regulation standards the manufacturers do not have to design their engines to control CO so the typical expectation may not hold. For this limited dataset and the number of variables a difference of 15% is probably well within statistical probability. While all of the backhoes were John Deere's with essentially the same horsepower, the wheel loaders consisted of a 120 hp Tier 2 Cat, a 225 hp Tier 3 John Deere, and a 273 hp Tier 3 Komatsu.

Parameter	Units	Mode	Wheel Loader		Backhoe	
			Tier 2	Tier 3	Tier 2	Tier 3
Fuel	g/s	Idling	0.64	0.88	0.49	0.48
		Working	3.02	5.18	1.96	3.70
CO	g/kg	Idling	12.71	15.44	17.41	10.41
		Working	10.00	17.31	8.77	6.65
HC	g/kg	Idling	2.33	1.86	4.08	1.80
		Working	1.41	0.50	2.57	1.27
NO _x	g/kg	Idling	42.42	37.38	47.15	45.66
		Working	23.07	26.44	26.73	16.47
PM	g/kg	Idling	0.50	0.38	0.32	0.10
		Working	0.90	0.62	0.35	0.15

Table 4-2: Typical Emission Factors for Each Pollutant under Idling and Working Conditions

ORE Graphical User Interface

A graphical user interface was developed for the ORE model using Visual C# and the .NET 3.5 Framework. The .NET 3.5 Framework was released in 2007 and can be installed on Windows XP, Vista and Windows 7. The ORE GUI provides a user friendly interface for running single vehicle emission estimations.

The main window of the GUI is presented in Figure 4-7. In this window, the user selects the equipment type and the amount of diesel fuel consumed in gallons. The application

then calculates the minimum and maximum possible running time for the equipment type based on fuel use rates at idle and during working conditions. The minimum value is based on the idle fuel rate and the maximum value is based on the working fuel rate. The user can then input the appropriate run time in the provided box or select the percent of time spent in idle mode or work mode using the provided sliders. If any of these three values is set (time in hours, percent idle time, or percent work time), the remaining two variables are calculated and updated. In addition to this, the Idling, Working, and Total outputs for Fuel, CO₂, CO, HC, NO_x and PM are calculated.

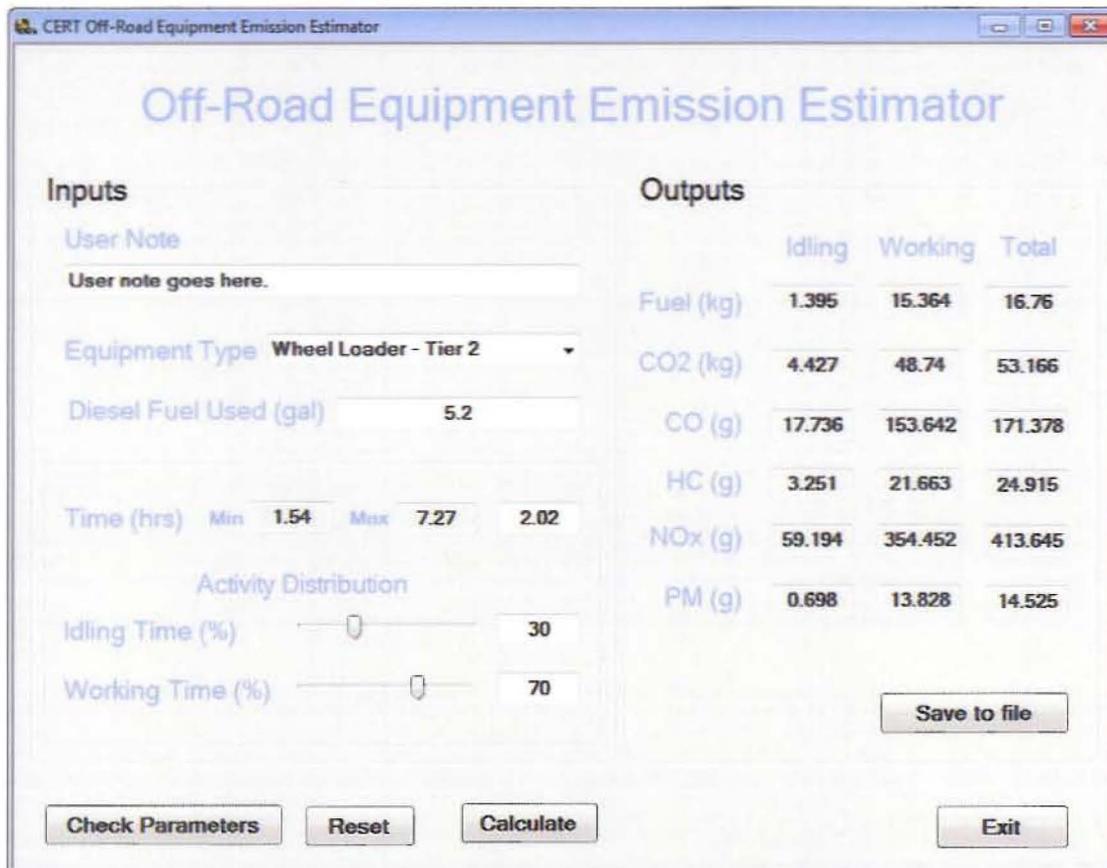


Figure 4-8: Main window for ORE model

The fuel use rates in grams per second, along with the fuel based emission rates can be viewed using the “Check Parameters” button which brings up the window in Figure 4-9. These values are presented for idle and work modes.

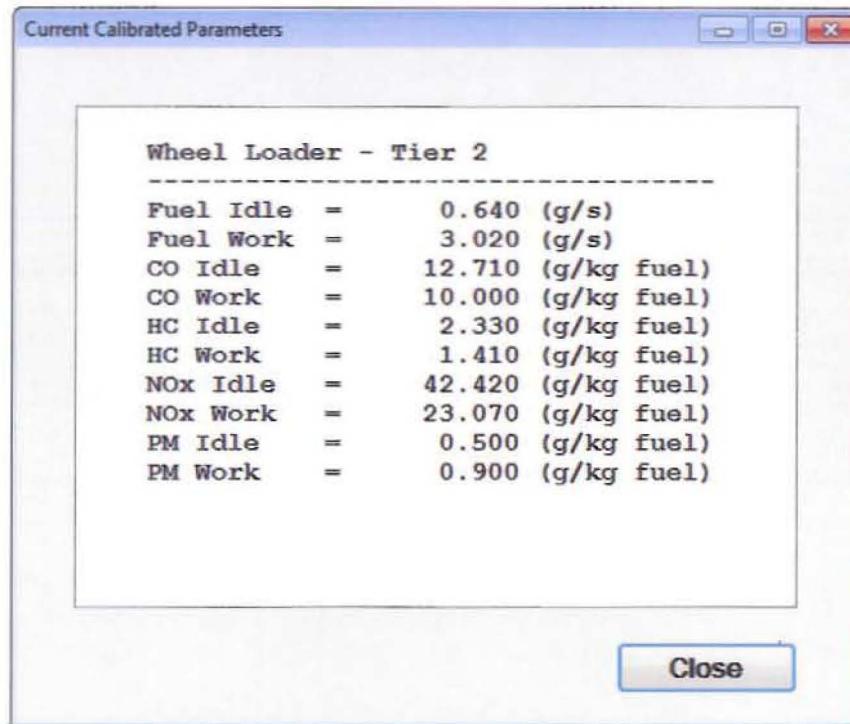
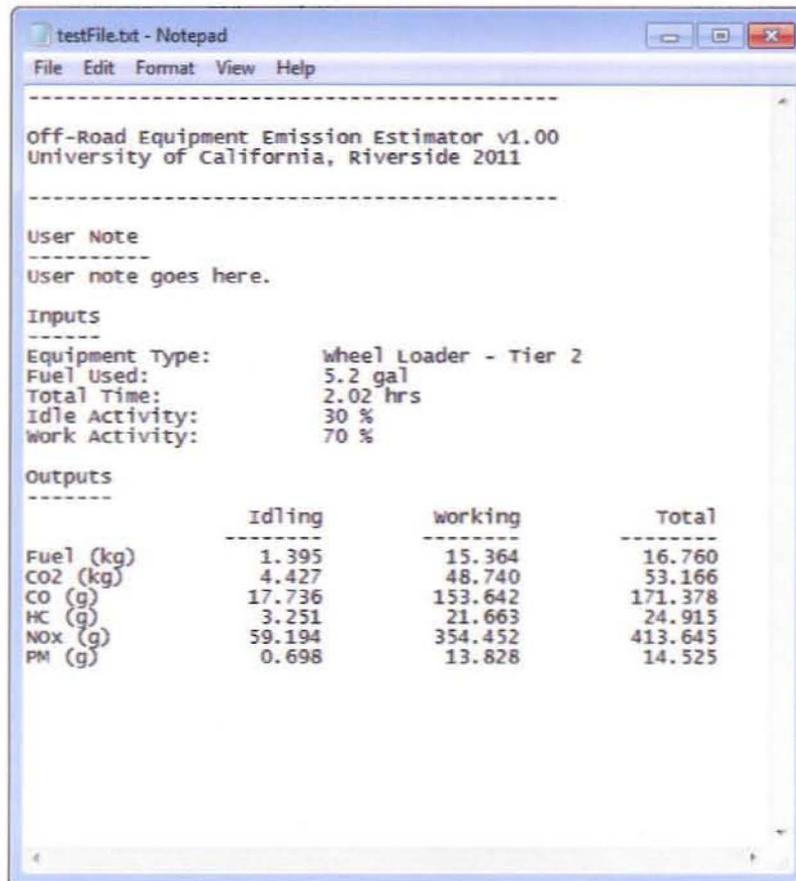


Figure 4-9: Current parameter display window for ORE Model

The "Save to file" button saves the output data to an ASCII text output file for which the user provides the name. An example output file is presented in Figure 4-10. The file's header section contains the program name, version number and credit information. Following the header section, the user note is referenced. The user note is specified on the main page and allows the user to add identifying information to the model calculation and output file. The input section presents the user inputs associated with the calculation and the output section present the fuel consumption and emission production for the idling and working mode as well as combined total.

Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment



```
testFile.txt - Notepad
File Edit Format View Help
-----
Off-Road Equipment Emission Estimator v1.00
University of California, Riverside 2011
-----
User Note
-----
User note goes here.
Inputs
-----
Equipment Type:      wheel Loader - Tier 2
Fuel Used:           5.2 gal
Total Time:          2.02 hrs
Idle Activity:        30 %
Work Activity:        70 %
Outputs
-----
              Idling      working      Total
-----
Fuel (kg)      1.395      15.364      16.760
CO2 (kg)       4.427      48.740      53.166
CO (g)         17.736     153.642     171.378
HC (g)         3.251      21.663      24.915
NOX (g)        59.194     354.452     413.645
PM (g)         0.698      13.828      14.525
```

Figure 4-10: Sample output file from the ORE model

5.0 References

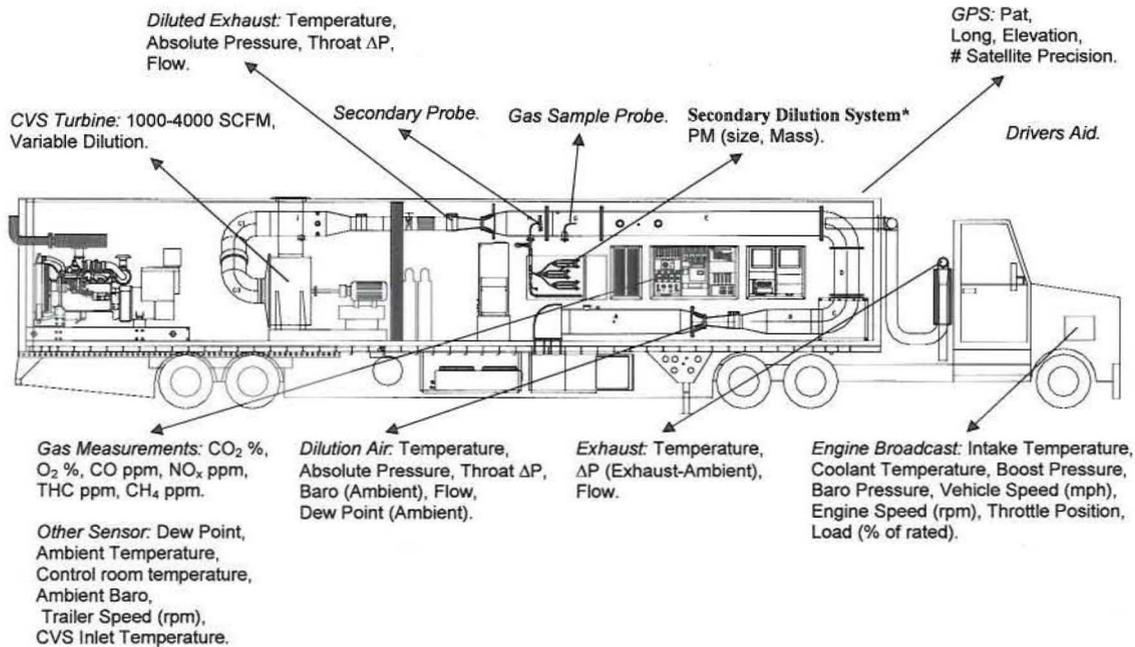
- Barth, M., Durbin, T. D., Miller, J. W., and Scora, G. (2008) Final Report, Evaluating the Emissions from Heavy-Duty Construction Equipment, Prepared for: California Department of Transportation (Caltrans) Division of Research and Innovation RTA 65A0197
- Frey, C. (2008) Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina. Technical Report for Research Project Number FHWA/NC/ 2006 – 55.
- Zhou, L., (2007) EMFAC Modeling Change Technical Memo: Revision of Heavy-Duty Diesel Truck Emission Factors and Speed Correction Factors. Technical memo from the California Air Resources Board, October, www.arb.ca.gov.
- Battelle, 1999. Heavy-duty truck activity data. Prepared for the Federal Highway Administration (FHWA), April. California Air Resources Board (CARB), 2000. Technical support document to public meeting to consider approval of revisions to the state's on-road motor vehicle emissions inventory, May. California Air Resources Board (CARB), 2003. EMFAC2002 v2.2, April.
- Clark, N.N., Kern, J.M., Atkinson, C.M., Nine, R.D., 2002. Factors affecting heavy-duty diesel vehicle emissions. *Journal of the Air & Waste Management Association* (52), 84–94.
- Cocker, D.R., Johnson, K.J., Shah, S.D., Miller, J.W., Norbeck, J.M., 2004. Development and application of a mobile laboratory for measuring emissions from diesel engines I. Regulated gaseous emissions. *Environmental Science and Technology* 38 (7), 2182–2189.
- Gautam, M., Clark, N.N., Wayne, W.S., Thompson, G., Lyons, D.W., Riddle, W.C., Nine, D.W., Satggs, B., Williams, A., Hall, T., Thiagarajan, S., 2003. Heavy-duty vehicle chassis dynamometer testing for emissions inventory, air quality modeling, source apportionment and air toxics emissions inventory. CRC Project No. E-55/E-59, Final Report, April.
- Lev-On, M., LeTavec, C., Uihlein, J., Kimura, K., Alleman, T.L., Lawson, D.R., Vertin, K., Gautam, M., Thompson, G.J., Wayne, S., Clark, N., Okamoto, R., Rieger, P., Yee, G., Zielinska, B., Sagebiel, J., Chatterjee, S., Hallstrom, K., 2002. Speciation of organic compounds from the exhaust of trucks and buses: effect of fuel and after-treatment on vehicle profiles. SAE Technical Paper, No. 2002-01-2873.
- Lloyd, A.C., Cackette, T.A., 2001. Diesel engines: environmental impact and control. *Journal of the Air & Waste Management Association* 51 (6), 809–847.

Shah, S.D., Johnson, K.C., Miller, J.W., Cocker, D.R., 2006. Emission rates of regulated pollutants from on-road heavy duty diesel vehicles. *Atmospheric Environment* 40 (1), 147–153.

Yanowitz, J., McCormick, R.L., Graboski, M.S., 2000. In-use emissions from heavy-duty diesel vehicles. *Environmental Science and Technology* 34 (5), 729–740.

Appendix A – Background Information on UCR's Mobile Emission Lab

Extensive detail is provided in Reference 1; so this section is provided for those that may not have access to that reference. Basically the mobile emissions lab (MEL) consists of a number of operating systems that are typically found in a stationary lab. However the MEL lab is on wheels instead of concrete. A schematic of MEL and its major subsystems is shown in the figure below. Some description follows.



Major Systems within the Mobile Emission Lab

The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from 1000 to 4000 scfm with accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 600kW. Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs for the primary tunnel.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH₄), total hydrocarbons (THC), CO, and CO₂ at a frequency of 10 Hz and were selected based on optimum response time and on road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are

suspended in the MEL allowing four test cycles to be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in the table below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

Gas Component	Range	Monitoring Method
NO _x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO ₂	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH ₄	30/100/300/1000 (ppmC)	FID

Summary of gas-phase instrumentation in MEL

Program Steering Committees (PSCs) / Technical Advisory Panels (TAPs)

PROGRAM STEERING COMMITTEE	Division	Staff Support	TAP Categories	Division TAP Coordinator	DRI Technical Representative
Design / Construction	Lead: Division of Design (Abbott) Support: Construction (Leja)	Division Staff Coordinators: Tim Craggs, Keith Robinson DRI Liaison: Homar Noroozi	Landscape / Erosion Control	Jack Broadbent, Doug Brown	Gloria Gwynne
			Roadway Design	Ray Tritt, Kevin Hanley	Fred Yazdan
			Construction	Chuck Suszko	TBD
Environmental	Lead: Division of Environmental Analysis (Norvell)	Division Staff Coordinator: Gregg Erickson DRI Liaison: Nick Burmas	Biology	Richard Hill	Harold Hunt
			Cultural Factors (Archeology, History, Community Impacts)	Glenn Gmoser	Harold Hunt
			Environmental Engineering (Vibrations, Noise, Hazardous Waste, Water Quality)	Bruce Rymer	Harold Hunt
			Environmental Management	Kelly Dunlap	Harold Hunt
Geotechnical / Structures	Lead: Division of Engineering Services (Pieplow)	Division Staff Coordinator: James Davis, Acting (Structures) Phil Stolarski (Geotechnical) DRI Liaison: Nick Burmas	Geotechnical	Mark William	Loren Turner Cliff Roblee
			Structures	Mike Keever	Cliff Roblee Tom Shantz
			Earthquake Engineering	Mike Keever	Cliff Roblee Tom Shantz
Maintenance	Lead: Division of Maintenance (Orcutt) Support: Equipment (Sri Balasubramaniam) Administration (Lewis)	Division Staff Coordinator: TBD DRI Liaison: Joe Horton	Employee Safety	Theresa Drum, Joel Allen	Bob Meline
			Winter Maintenance	Antonio Duran, Herby Lissade	Larry Baumeister
			Roadside	Parvis Lashai	Arvern Lofton
			Homeland Security	Rene Garcia	Azzeddine Benouar
Modal	Lead: Division of Mass Transportation (Perez) Support: Aeronautics (Cathey) Rail (Bronte)	Division Staff Coordinator: Jila Priebe Scott Sauer DRI Liaisons: Nancy Chinlund & Prakash Sah	Transit	Scott Sauer	Bruce Chapman
			Rail	TBD	TBD
			Aeronautics	Terry Barrie	TBD
Pavement	Lead: Office of Pavement (Benipal)	Division Staff Coordinator: Susan Massey DRI Liaison: Nick Burmas	Pavement Management Council	Susan Massey	Joe Holland
Planning / Policy / System Information	Co-Lead: Division of Transportation Planning (Choate, Acting)	Division Staff Coordinator: Rahul Srivastava (Planning) La Keda Huckabay (TSI)	Air Quality	David Ipps	Patrick Tyner
			Climate Change	Kevin Tucker	Patrick Tyner
	Co-Lead: Transportation Systems Information (Appleton, Acting)	DRI Liaisons: Nancy Chinlund Nicole Longoria	Community & Regional Planning	Marilee Mortenson Terry Parker	Bob Justice Mohamed Alkadri
			Complete Streets	Alana Hitchcock	Bob Justice
			Goods Movement	Debbie Nozuka Bruce Kemp	Matt Hanson Patrick Tyner
			System & Corridor Planning	Craig Wahl	Bob Justice
Transportation System Information & Modeling	La Keda Huckabay	Bob Justice			
Right of Way and Land Surveys	Lead: Division of Right of Way Land Surveys (Green)	Division Staff Coordinator: Mark Turner DRI Liaison: Homar Noroozi	Right of Way	TBD	Randy Woolley
			Land Surveys	Kevin Akin	Randy Woolley
Rural	Lead: District 2 (Lamkin)	Division Staff Coordinator: Ian Turnbull DRI Liaison: Sean Campbell	Rural	Ian Turnbull	Sean Campbell
Transportation Safety and Mobility	Lead: Division of Traffic Operations (Copp)	Division Staff Coordinator: Khanh Vu, Monica Kress DRI Liaison: Greg Larson	Mobility	Monica Kress	Pete Hansra
			Roadway Safety Appurtenances	Randy Hiatt	John Jewell
			Traffic Safety	Craig Copelan	Joel Retanan